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The Potential for Biomimetic Solar Energy

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The Potential for Biomimetic Solar Energy

by

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The Potential for Biomimetic Solar Energy

by

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The purpose of this thesis is to explore the potential for integrating biomimetic thinking into the design and implementation of photovoltaic energy systems in a way that promotes ecological health, economic feasibility, and equal access to cleaner energy. Photovoltaic energy production is among the most promising renewable energy sources, however, current conventional photovoltaic systems exhibit a number of shortcomings. Steering innovation toward socio-technical systems that are integrated with ecological systems will help support human needs without inhibiting larger ecological function.

This investigation began with the construction of a conceptual biomimetic lens from a foundation of literature related to biomimicry in the built environment. Next, the underlying elements, interconnections and functions of both the ecological systems involved in photosynthesis and socio-technical systems related to photovoltaic energy production were defined and examined. The biomimetic lens was then applied to each system to envision biomimetic approaches to address shortcomings of current conventional photovoltaic systems. The suggested approaches aim to address shortcomings in the design, manufacture, and implementation of photovoltaic systems in ways that mimic key principles found in biology and ecology. Since the success of ecological systems is embedded in the nesting of interrelated systems, the biomimetic lens was applied at multiple scales: the chloroplast/solar cell, the leaf/solar panel, the plant/solar array, and the ecosystem/community scale.

The results of this study both suggest the direction of further research in the development of biomimetic solar energy systems and provide insight into the effectiveness of biomimetic thinking as a strategy for designing equitable, economical, and ecologically sound systems.

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1 Introduction

The success of nature's ability to create conditions that can sustain life is deeply embedded in its 3.8 billion years of evolution and is seen in its resiliency and adaptability. Although the human-built world exists within the natural world and must abide by the same physical laws as non-human nature, much of modern society functions under the assumption that we do not. When searching for the answers to how human development can become as resilient and conducive to life as non-human growth, it is hard to imagine a more sensible path than taking advantage of the socially constructed divide we perceive between nature and society, pointing to the non-human world as a mentor, and mimicking the solutions that the non-human world has already tested over time. Biomimicry, the design of human systems and artifacts that mimic natural systems and organisms, has great potential to influence the future of human development in a way that acknowledges its position within the natural world.

Although there are a vast variety of applications of biomimicry toward a number of noble (and less noble) goals, I will focus on the potential for biomimicry to become unique strategy to help the human-made world achieve environmental sustainability within existing social and economic conditions. Biomimicry is different than many other approaches to sustainable design because it combines technological innovation with our deep inherent connection to 'nature' to challenge assumptions about how and why the built environment is made and used (Zari, 2010). Biomimicry is a path to sustainability that embraces technology. Technology, as defined by MacKenzie and Wajcman, includes physical artifacts as well as knowledge and processes (Wajcman & MacKenzie, 1999). Despite the potential for a sustainable future through biomimetic design, there have been few attempts to apply biomimetic principles across scales to incorporate whole systems that are embedded in local environmental and social conditions. Applying a biomimetic lens as a means of achieving sustainability requires acknowledging the integration of both social and environmental elements as interconnected pieces of one system. Strategies involving cooperation and co-existence between these seemingly disparate worlds can be developed by looking to the non-human environment's inherent ability to weigh the needs of the individuals against the needs of the whole system to ensure sustainable functioning.

Despite the intention of Otto Schmidt, who coined the term *biomimicry*, to define biomimetics as a "despecialization" that would transcend disciplines, today's biomimetics typically fall into one of two categories of specialists: natural scientists advocating for the use of a particularly remarkable natural process or system found in nature (investigation) or designers seeking solutions to a particularly difficult problem in the built world (application). In this paper, I will use my unique position as an academic with equal interest and experience in design and the natural sciences to give near equal weight to both the investigation and the application of biomimicry.

In this thesis, I will test the biomimetic hypothesis by investigating a system that touches nearly all elements of today's society either directly or indirectly: energy production. The processes associated with energy and its accessibility (or lack there of) influence the quality of life measured by the standards of today's consumer culture as "all economic activity relies on the physical and chemical conversion of materials from one form to another, and the conversion of fuels into the energy needed to distribute and consume the resultant products" (Scheer, 2004, p. 3). The design and implementation of the electricity production and distribution system (the grid) was largely considered a great success in its time. However, different groups interpret the success of technology differently. Bijker and Pinch refer to this concept as "interpretive flexibility" (Bijker, Hughes, & Pinch, 2012). Bijker and Pinch assert that "social groups give meaning to technology and that problems…are defined within the context of the meaning assigned by a social group or combination of social groups" (Bijker, Hughes, & Pinch, 2012, p. 6). These groups may be distinguished based on physical boundaries (geography), cultural boundaries, economic boundaries, or temporal boundaries or some combination of distinguishing features. The current energy production and distribution system may have been interpreted as successful at the time of its conception by certain relevant social groups, but not by all. Several scholars working in nineteenth century Europe recognized the fundamental problems with nonrenewable fuel use upfront.

Since then conditions affecting the physical electrical production and distribution system have changed – how we use energy, when we use it and how much we consume – and consequently the state of the system has grown even more concerning to current relevant social groups. These changes to conditions are due to countless reasons from changes in climate, to technological innovation, to changes in standards of living. Within these new conditions, perceptions of the energy system's success are changing (or have already changed) among many social groups. To use the language of Pinch and Bijker, this change may suggest we have accepted a false acceptance of "closure." In science, closure occurs when "a consensus emerges that the 'truth' has been winnowed from the various interpretations" (Bijker, Hughes, & Pinch, 2012, p. 6). In science technology studies (STS) "closure" indicates the disappearance of problems associated with the technology to the point that the development is stabilized (Bijker, Hughes, & Pinch, 2012). A false acceptance of the closure of large-scale energy production has inhibited a more rigorous pursuit of a more sustainable and equitable power source. However, the state of solar energy technology today is the product of the refusal of certain scholars and engineers to recognize closure. When they began searching for alternatives they quickly found that solar energy could produce 'unlimited power at almost no cost', or so they thought (Perlin, From Space to Earth: The Story of Solar Electricity, 1999). From the International Space Station to the rural villages of West Africa, photovoltaic systems have been installed as solutions where no other solutions could be found. However, these piecemeal solutions will not be enough to ensure a sustainable society.

The majority of all current solar energy produced and consumed comes from photovoltaic arrays made of crystalline silicon semiconductors. There are many shortcomings of conventional crystalline silicon photovoltaic systems that prohibit urban communities from producing the energy necessary for them to become self-sustaining without causing ecological damage, economic strain, or inequality of energy access. The current technologies of the panels themselves pose several problems related to material extraction and eventual disposal. The list of chemical compounds, extreme temperature requirements, and hazardous wastes that must be cautiously disposed of are cause for questioning the 'clean energy' designation that is often applied to photovoltaics. In this thesis, technologies that reduce but still pose some threat to both the natural environment and to the health and safety of human communities are not considered sustainable. There are also productivity barriers related to both the electricity-generating processes and the disparity between the generation capacity and consumption demand. In the modern built environment, energy demand is in no way connected to locally (site or immediately site adjacent) available energy. In the non-human environment, biological elements have existed, currently exist, and will continue to exist within the constraints of spatially and temporally available materials and energy – namely the solar radiation that drives all functioning. Until these and other shortcomings of current conventional photovoltaic systems are addressed, the modern world lacks the ability to develop in a sustainable manner using photovoltaic energy.

In this thesis, I will investigate whether integrating biomimetic thinking at various scales into the design, implementation, and assessment of photovoltaic systems offers strategies that address the ways in which conventional photovoltaic systems fall short of ecological health, economic feasibility, and equal access to cleaner energy. The results of this investigation includes both a hypothesis that it is possible to develop a biomimetic system of energy production that would address these concerns and a proposal for further interdisciplinary research.

2 Research Design

The study of biomimicry calls for the development of a unique system of inquiry and a creative approach to performing analogy research. This chapter will outline both the methodology in which this study was conducted and the specific strategic methods that were implemented.

2.1 Methodology

This study was conducted within a constructivist system of inquiry. Constructivist thought asserts that the physical world exists, but knowledge and understanding of the physical world is relative to groups or individuals. To borrow from system scientist Bela Banathy: "A world-view is like a lens through which we perceive the landscape of life that becomes our reality. Those who look through the lens of the previous era see their own reality very differently from those who use the lens that the new era has crafted" (Banathy). In this paper, I acknowledge the equally sound value of technological, social, and biological systems. By switching, sharing, and overlapping the lenses held by designers of the build world, investigators of the natural world, and the inhabitants of the sociopolitical world a new reality is created.

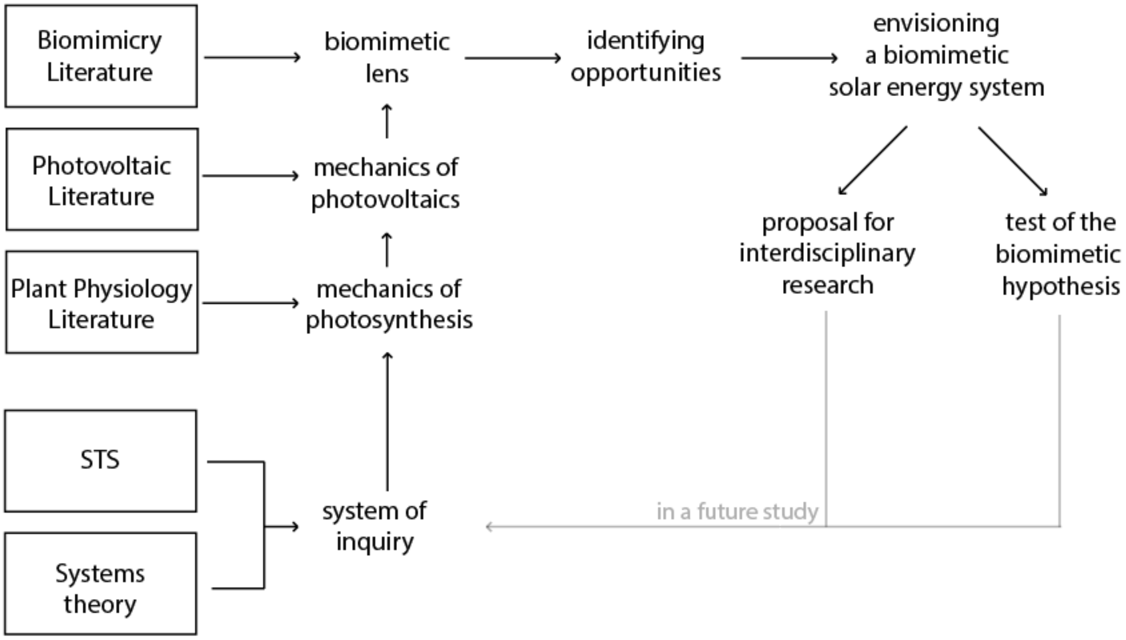


Figure 01. Research design
Developed by author

Although the constructivist system of inquiry is not limited to the assumptions of a scientific reasoning, the nature of constructivism recognizes multiple processes for understanding the world including scientific reasoning. In the review and quest for understanding plant physiology, research into plant systems was conducted within a scientific system of inquiry. Although I recognize that the due to my own interaction with the subjects the knowledge gained has not been objectively attained, the strategic methods were borrowed from scientific reasoning. A similar approach was taken to understanding the mechanics of current conventional photovoltaic technologies, however, the study of photovoltaics takes social and economic structures into consideration. The application of the newly constructed biomimetic lens incorporates multiple ways of knowing.

2.2 Strategic Methods

The research design consists of three areas of data collection: a biomimicry literature review resulting in the construction of a new biomimetic lens; a photovoltaic literature review resulting in the understanding of the essence of photovoltaics and their role in a sustainable future; a detailed overview of the systematic characteristics of photosynthesis in plants in the Midwest region. Finally, the biomimetic lens will be applied to suggest characteristics of a biomimetic solar energy system.

2.2.1 Literature review strategies

My research begins with the review of biomimetic design literature to develop a synthetic working definition of biomimicry and construct a biomimetic lens through which to interpret the next two sets of literature. This lens includes a system for measuring the success of a technology based on it’s ability to promote environmental protection and measuring the validity of utilizing biological principles as design guidelines based on their capability to perform in a way that is economically viable. After completing a review of the biomimicry literature and constructing a lens, the literature review on photovoltaics was conducted and the essential characteristics of an effective solar energy system were determined. Finally, photosynthesis-related characteristics of plants were studied through a review of the current literature on photosynthesis.

2.2.2 System analysis and analogy research strategies

As outlined in Petra Gruber's *Biomimetics in Architecture* analogy is an important strategy in biomimetic research. Translating concepts from one field (biology) to another (design) is made possible through abstracting complex systems and comparing through analogy. To avoid trivial analogies that are abundantly found in shallow biomimicry, the analogy research conducted in this thesis looks beyond analogous forms and procedures to suggest opportunities for mimicking the underlying development processes, function and purpose, and environmental and social impact.

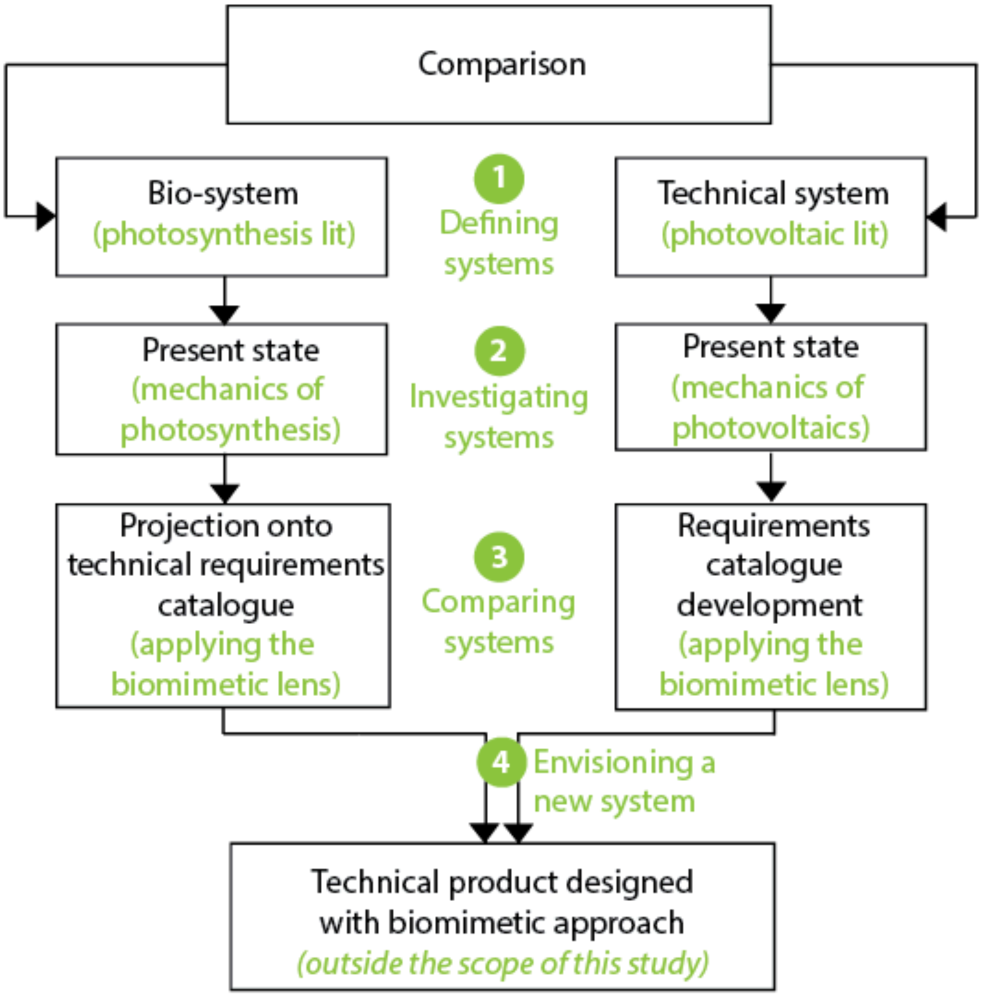


Figure 02. Analogy research as explained by Nachtigall via Gruber.
Based on content from (Gruber, 2011)

A systems view is critical to understanding and envisioning a new technological system. Technological historian Thomas Hughes "stresses the importance of paying attention to the different but interlocking elements of physical artifacts, institutions, and their environment and thereby offers an integration of technical, social, economic, and political aspects" (Bijker, Hughes, & Pinch, 2012, p. xlii). To begin the analogy research, a systematic analysis of both the biological system of photosynthesis and the sociotechnical system of photovoltaic energy generation was conducted to identify key elements, interconnections and functions that either merit mimicry in the case of photosynthesis or are in need of reinvention in the case of photovoltaics.

According to Diana Wright and Donella Meadows there are three different components to any system: elements (defined by their attributes), interconnections, and function or purpose (Meadows & Wright, 2008). Elements are the *nouns* in the system; they are the people, places, things, and ideas that exist within the system. Elements can be physical objects or intangible concepts. Elements have boundaries, and may even contain their own nested system within the larger system being observed. Elements are not only defined by their general existence, but also by the attributes that they possess. Attributes are the *adjectives* of the system. Attributes describe the characteristics of the elements. Interconnections are the *verbs* of the system. Interconnections describe element-to-element interactions as well as the interaction between a single element and the system function as a whole. The function (in natural systems) or purpose (in technological systems) is the overall result of the existence of the elements and their interactions with each other. According to Wright and Meadows, "purposes are deduced from behavior, not from rhetoric or stated goals" (Meadows & Wright, 2008, p. 14).

The biological system in which photosynthesis occurs was be studied to identify naturally occurring patterns in the relationships between elements of the system, the environmental conditions in which the system exists, and the system's function. For the purposes of this study, the system will be looked at in four nested subsystems of increasing scale. The result of this exercise was a system map describing elements, interconnections, and functions that will serve as a control against which to compare a hypothetical biomimetic solar energy system.

The sociotechnical photovoltaic system was studied in a similar manner. However, sociotechnical systems vary from biological ones in many ways, and consequently their study should also differ. Perhaps the most apparent difference is the inclusion of social factors in sociotechnical systems. Technological systems have an inherent social component since technology requires human action. Although this study does not have a strong focus on the intricacies of social aspects of the photovoltaic energy system, their presence and importance is recognized. Sociotechnical systems, like biological systems, tend to be organized and managed hierarchically. As suggested by science and technology studies scholar Thomas Hughes, the process used in this thesis for studying the photovoltaic system makes clear that each system studied is both a subsystem as well as a meta system (Bijker, Hughes, & Pinch, 2012). Following the analysis, the larger photovoltaic system will be reimagined systematically by identifying opportunities for analogous development at predetermined scales and points of time in the lifecycle of the system. The hypothesized success of the reimagined system is determined based on its predicted ability to produce energy at a socially and economically acceptable level while operating with an environmental impact equivalent to that of the biological system.

3 Literature Review

This section looks at three distinct bodies of literature: biomimicry (including both general biomimicry theory and biomimetic applications in the built environment), current and emerging photovoltaic technology, and plant physiology related to photosynthesis.

3.1 Biomimicry literature

3.1.1 History of bionics and biomimicry

Modern day biomimetics recognize the extent to which creating artifacts and technologies to mimic natural organisms and processes has been integrated into design since the first artifacts that were created. The majority of biomimetic scholars also agree that early human civilizations who were not misled by the perceived socially constructed divide between the built environment and the non-human natural environment were successful biomimetics long before the field of biomimicry had been established. Human civilization began to grow apart from the non-human environment experientially with industrialization and physically with urbanization, but there is evidence of biomimetic thinkers interspersed with industrial thinkers throughout human history. Some recognize Leonardo DaVinci and his flying machines as early biomimetic mechanical engineering. Biomimetic material science can be seen in the work of French entomologist Rene Antoine Reamur who, in the early 18th century, suggested that wasps' use of wood pulp would make a good alternative to the then common cotton-pulp paper (Pawlyn, 2011).

In the early twentieth century, most biomimetic design (though not yet labeled as so) found in the post-industrial West was concerned with large-scale industrial applications including both land and water locomotion, and were focused only on how learning from non-human systems and organisms could help them reach their highly industrial goals faster and more effectively (Gruber, 2011). In "biomechanics" there was little or no association between mimicking natural forms, processes, and systems and the overarching goal of environmentally beneficial, or even *benign*, development. Instead, pre World War II biomimetics were preoccupied with the application of observed forms that were largely "too direct and uncritical" (Gruber, 2011, p. 25).

Post World War II, biomimetic-like design shifted from the preoccupation with application to devoted investigation of the relationship between form and function in the development of natural processes and systems. In 1942, Scottish biologist D'Arcy Thompson published *On Growth and Form*, which discussed *how* form in organisms develops in an accessible way (Gruber, 2011). *On Growth and Form* is still highly regarded and even deemed the "bible for the development of form and structure of living organisms" (Gruber, 2011, p. 26). Several other biologists followed his lead and an accessible knowledge base of form-function relationships in nature began to develop.

In 1960, when US Air Force Major J.E. Steel organized a conference entitled "Bionics Symposium: Living prototypes – the key to new technology," a solid field around nature-inspired design began to form (Gruber, 2011). Major Steel outlined bionics as "[the] science of systems that work like or in the same manner as or in a similar manner to living systems" (Von Gleich, Pade, Petschow, & Pissarskoi, 2009, p. 16). The study of bionics continued to grow throughout the mid-twentieth century to emphasize the importance of both the investigation into biological processes and purpose of applying the findings that resulted – to improve old technologies or discover superior ones (Von Gleich, Pade, Petschow, & Pissarskoi, 2009). In the US, the field of bionics remained, for the most part, within the realm of robotics and other mechanical replacements for living matter, body parts, or tissue (Gruber, 2011). In Germany the term bionics stuck as the concept itself continued to expand to include applications outside of robotics. In the US, one bionics scholar, Otto Schmitt, recognized some restrictions of bionics and opted for a new term: biomimicry.

Although the concept of biomimetic design has been applied to the built world since prehistoric times and the first group of biomimetic thinkers convened under the guise of bionics, the term 'biomimicry' first appeared in scientific literature courtesy of Otto Schmitt in 1963. At a bionics conference in Dayton just three years after Steel coined the term bionics, Schmitt had already begun to question its development, stating:

> Let us consider what bionics has come to mean and what it or some word like it (I prefer biomimetics) ought to mean in order to make good use of technical skills of scientists specializing, or rather, I should say, despecializing into this area of research" (Vincent, Bogatyreva, Bogatyrev, Bowyer, & Pahl, 2006, p. 471).

Six years later Schmitt used "biomimetics" in the title of one of his papers, and by 1974 it was officially added to Webster's Dictionary (Vincent, Bogatyreva, Bogatyrev, Bowyer, & Pahl, 2006). Throughout the remainder of the 20th century, biomimetics began to permeate a variety of fields. In the 1980's biomimetic design became particularly popular among material scientists. In the 1990s, the field began to see a shift in participating disciplines from those addressing application to those capable of understanding and uncovering complex ecological forms, processes, and systems – the natural scientists.

In 1997 Janine Benyus wrote her book entitled *Biomimicry: Innovation Inspired by Nature*, which, due to its accessible language and vivid imagery, began to attract widespread attention in a variety of fields. It also began to transform biomimicry into more than borrowing helpful principles from nature to further technology – Benyus's biomimicry broadened the focus to include learning from nature in both a technical and experiential way. Benyus's biomimicry is just as much about inspiration as it is about investigation. Steven Vogel, a contemporary of Benyus and a zoologist by trade, also wrote of the opportunities for nature-inspired design in *Cats Paws and Catapults*, but with a slightly different approach (Vogel, 1998). Vogel's work tends to focus more on stripping down nature to the nuts and bolts to identify opportunities rather than the romanticized nature seen in the case studies presented by Benyus. His focus is specifically on engineering applications, in contrast to Benyus's broad cross-section of disciplines. Both Benyus and Vogel's work toward bridging the discipline gap led architects and industrial designers, whose jobs regularly position them to work at the intersection of several different disciplines, to experiment with the idea of biomimicry. Not only does biomimicry suggest a number of practical technical solutions to taxing environmental and economic challenges, but it also has a poetic quality that supports the architect's affinity for creating places of meaning.

The focus of this investigation is biomimicry as it applies to powering the built environment. Although there are a number of practicing biomimetics in the field of architecture, in the Western world two architectural scholars have appeared to make significant contributions to the literature as seen in my own investigation: Michael Pawlyn and Petra Gruber. Michael Pawlyn's *Biomimicry in Architecture*, published in 2011, reads almost as a manifesto, opening: "We are entering the Ecological Age, and it is the contention of this book that many of the lessons that we will need for this new era are to be found in nature itself" (Pawlyn, 2011, p. 1). Throughout the piece, Pawlyn envisions a biomimicry that should assessed based on both how well the design performs as well as its beauty. If Pawlyn is to biomimetic architecture what Janine Benyus is to investigative biomimicry, then Petra Gruber is the Steven Vogel of the biomimetic architecture world. Dissimilar to Pawlyn or Benyus's integration of performance and poetics, Gruber emphasizes the evolution of biomimetic thinking and its application.

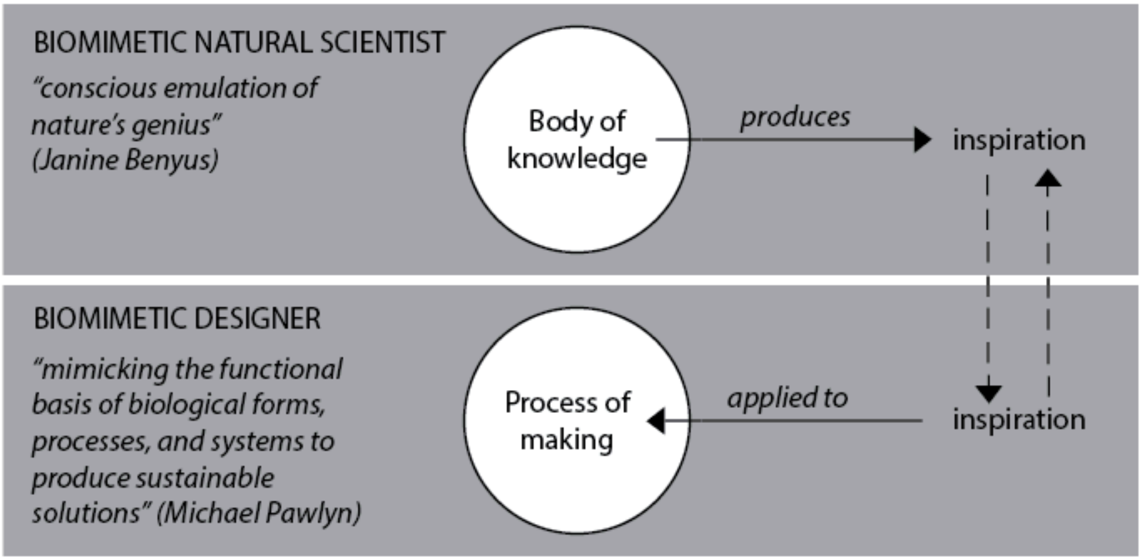


Figure 03. Approaches to biomimicry: Top-down (application) and bottom-up (investigation) approaches to biomimicry
Developed by author

Perhaps in contrast with Otto Schmidtt's emphasis on biomimicry as a "despecialization," Julian Vincent is among a few scholars that claim a *title* in the discipline of biomimetics rather than a focus or interest in biomimicry and a title in another, more established discipline. Among Vincent's most important contributions to the field of biomimicry is the development of BioTRIZ (which has also driven the inspiration of this paper). BioTRIZ as a tool for translating concepts and solutions from one discipline to another will be discussed further in the final section of the biomimicry literature review in "Biomimetic Tools."

Not only are there different methods for applying biomimicry across disciplines, but there is also a different interpretation and application across cultures (Gruber, 2011). In the UK biomimetics typically lives in the discipline of engineering, but is limitedly active in other fields. In Germany there are stronger ties to the life sciences that work in collaboration with industrial partners. In both Japan and China biomimicry is most prevalent in robotics, nanotechnology, and medical research. In the US applied biomimicry is often found in the fields of robotics, material science and nanotechnology (Gruber, 2011).

3.1.2 Transdisciplinary nature of biomimicry

The field of biomimicry was transformed as it broke out of segmented professional and academic structures and became a tool for transcending traditional disciplinary boundaries. However, "the influence that life sciences can have on other disciplines is highly dependent on the publication of universally understandable research output" (Gruber, 2011, p. 22). Historically, there are a handful of thinkers who translated complex environmental concepts into accessible forms including Ernst Haeckel and Karl Blossfeldt. The unique perspective and artistic abilities of Ernst Haeckel allowed him to translate his life's work in biology into sketches and diagrams that communicated the concepts he was studying in a way that resonated with the public and experts in other fields. Although his work did not change the course of biology itself, it was revolutionary to many designers who used the information Haeckel presented to create some of the first zoomorphic designs (Gruber, 2011).

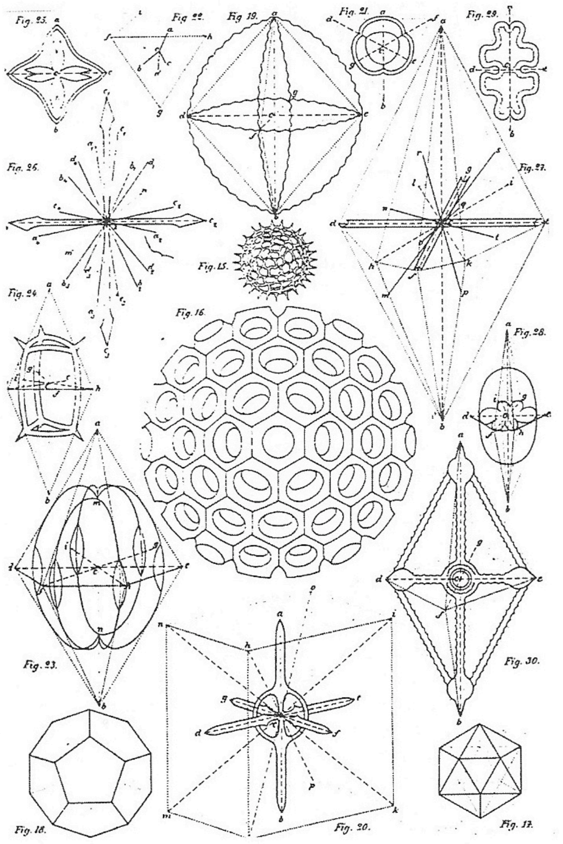


Figure 04. Ernst Haeckel, ideal basic forms
(Gruber, 2011, p. 23)

Janine Benyus fulfilled this role in the most recent wave of biomimicry, however, her art was with words rather than the visual art created by Haeckel and Blossfeldt. Benyus graduated from Rutgers University with degrees in both natural resource management and English literature – preparing her to understand the complexities of the natural sciences and effectively communicate them to broader audiences (Benyus, 1997). Her biocentric approach looks first to nature, recognizes successful strategies, and tells the stories of the potential they might have in the design and development of the built environment.

Benyus wrote that biomimetics "work at the edges of their disciplines, in the fertile crests between intellectual habitats" (Benyus, 1997, p. 4). The literature on biomimicry comes from a variety of fields, and each discipline frames problems and implements biomimetic solutions differently. Early biomimetic thinkers, like Otto Schmitt came from engineering rather than the natural sciences. Engineers in the field of bionics look at human problems whose solutions have thus far eluded them, and they look to nature for technical expertise. Engineers generally take an anthropocentric approach to applying biomimetic thinking to solve human problems. Biomimetic engineers can identify specific solutions in nature and applying them to human systems or artifacts. The engineer's approach has been effective, but limited in that their understanding of the larger biological contexts is limited. Nature works effectively because of the nesting of systems at a variety of scales, and the natural-scientist-biomimetic can generally think in that way more easily.

After biomimicry had the time to permeate into the design disciplines, architects and industrial designers became biomimetics naturally. As expressed by Petra Gruber,

> The generalist approach that architects inevitably have to take when designing buildings qualifies them to work in biomimetics. Their usual working practice involves contact and cooperation with highly specialized consultants and professionals. Their specific approaches, ideas, and the requirements of their respective profession have to be integrated into one single project (Gruber, 2011, p. 41).

Therefore, although architects do not necessarily have a strong background in natural sciences, their experience in coordinating information for a variety of disciplines in a single coherent project makes them excellent biomimetics. Authors Michael Pawlyn and Petra Gruber are among those who look at architecture past and present through a biomimetic lens to identify best practices and possible directions for the future of biomimetic architecture.

3.1.3 Subfields of biomimicry

Since the field of biomimicry is vast and its boundaries are largely undefined, many biomimetic scholars have attempted to distinguish between subfields. Although there is consensus that identifying subfields of biomimicry is necessary to study and further the field, there is not consensus as to how the field should be divided.

Several authors suggest distinguishing biomimetic principles and practices on the basis of scale; however, they do not agree on the granularity or designation of each scale as seen in Table 01. Architects and natural scientists tend to break up the scales by what is being mimicked – in other words, using natural science terms. Architect Malbrit Pederson Zari, the largely architecture-focused research team at Terrapin, and Volstad all identified three scales based on the scales found in nature: organism, organism's behavior, and entire ecosystem. The organism scale involves mostly mimicking physical things in order to create tangible objects. Mimicking an organism's behavior involves non-tangible actions. The ecosystem scale includes both the creation of tangible objects and the relationships/ actions between these objects. From a mechanical engineer's perspective, the issue of scale in biomimicry is divided in terms of application rather than source of inspiration. John Reap identifies subfields on a more granular level: material, component, assembly, product, system, and ecosystem. Gruber's attempt to find distinct subfields within biomimicry was slightly different in that she did not use the application or inspiration, she used terms that got at the essence of both sides.

Zari		Terrapin	Reap	Volstad	Gruber
Organism	Form	Form	Component	Natural form	Structural
	Material		Material		
	Construction		Assembly		
			Product		
Organism behaviors	Method	Process		Natural process	Procedural
Ecosystem	Strategies	Ecosystem	System	Holistic/ ecosystem	Informational
	Function		Ecosystem		
			Non-holistic		

Table 01. Subfields of biomimicry
Developed by author

Throughout the literature, there was a prominent theme among biomimetics from nearly every discipline that was included – the difference between a deep or holistic biomimicry and a shallow, reductive, or non-holistic biomimicry. According to Reap, holistic biomimicry is reliant on the search for and application of explanatory principles and involves careful observation, translation of concepts and incorporation of concepts into the physical product (Reap, Baumeister, & Bras, 2005). This is not another distinction from the aforementioned form, process, and ecosystem categories. Instead holistic v. non-holistic is dependent on how the design process is carried out. Non-holistic biomimicry "focuses solely on the imitation of few features or functions of particular organisms or biological processes, whereas, holistic use of biomimicry is a measure to achieve ecologically sustainable products" (Volstad & Boks, 2012, p. 191).

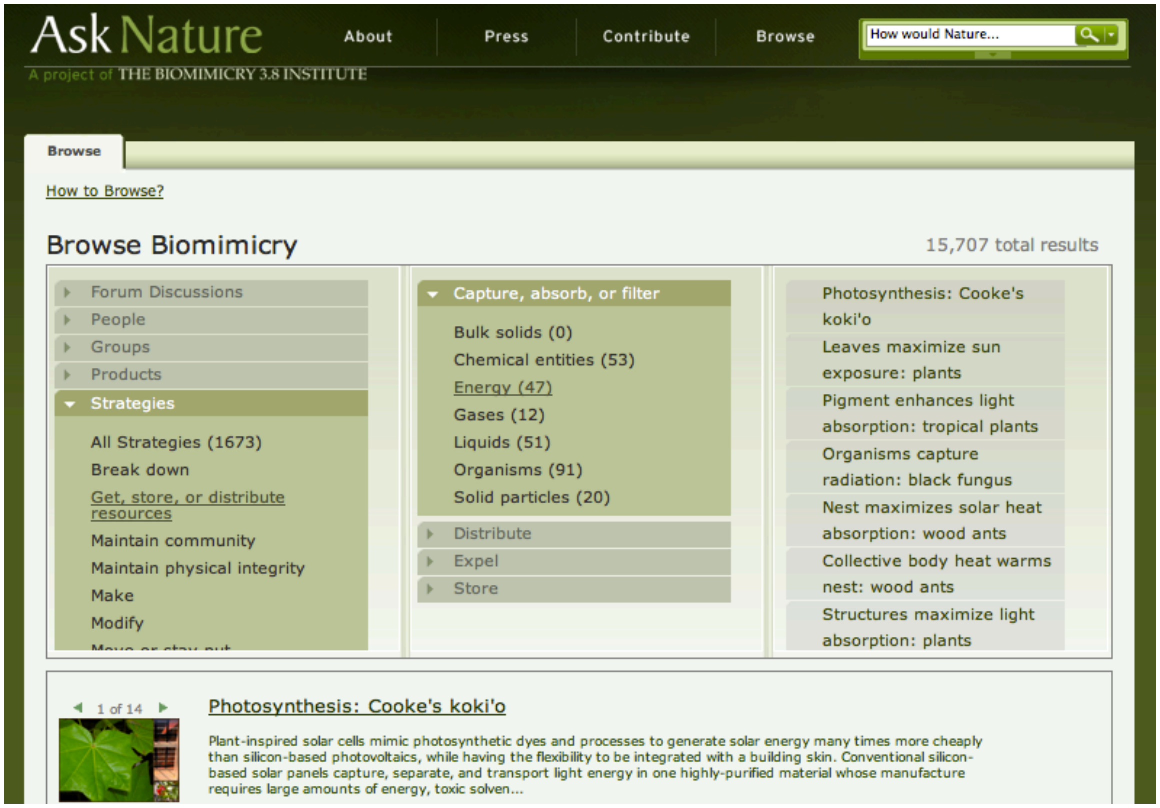
In many cases, the issue of time span considered determines whether a strategy is viewed as biomimetic by the designer or the researcher. Zari looks at biomimicry as a potential strategy for mitigating climate change caused by the design and function of the built environment (Zari, 2010). Organismal/structural/material biomimicry would be applied to increase energy efficiency and reduce the demand for emission-producing forms of energy. Behavioral/procedural/process biomimicry might mean looking at biomimicry for carbon storage. Holistic/ecosystem/informational biomimicry might look instead at how to replace the use of fossil fuels altogether.

3.1.4 Biomimetic tools

Though there is potential for biomimicry to become a sustainable solution, there are barriers related to teaching the process of biomimetic design, replicating the design process to make a larger impact due to the complexities of the problems at hand, and the interdisciplinarity of the solutions. This section will discuss three tools that have been developed to transform biomimicry from a design concept into a tool: a public database for design inspiration called AskNature, a systematic procedure for informing biomimetic design methods called BioTRIZ, and a method for assessing the success of biomimetic design known as the Living Building Challenge.

Inspiration: AskNature

AskNature.org emerged from the need for biomimetic design professionals to access relevant and digestible information on biological organisms and systems. The resulting product is a free, public database that translates biological concepts (typically from peer reviewed journals) into common language and categorized by function using the 'Biomimicry Taxonomy' (Deldin & Schuknecht, 2014). The Biomimicry Taxonomy was developed in collaboration with biologists and design professionals and is characterized by four levels of identification: group, subgroup, function, and strategy. As of January 2013, there were 8 groups, 30 subgroups, 162 functions, and over 1,600 strategies in the database (Deldin & Schuknecht, 2014).

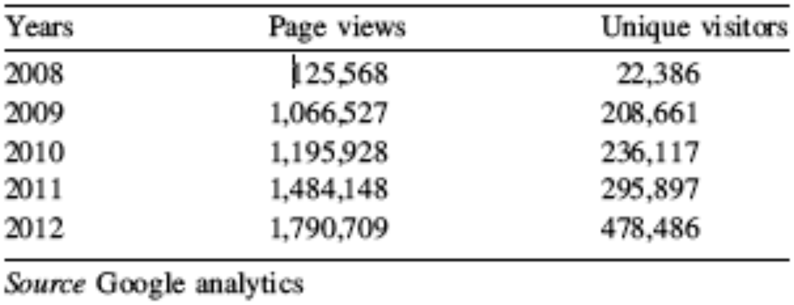


Photosynthesis: Cooke's koki'o

Plant-inspired solar cells mimic photosynthetic dyes and processes to generate solar energy many times more cheaply than silicon-based photovoltaics, while having the flexibility to be integrated with a building skin. Conventional silicon-based solar panels capture, separate, and transport light energy in one highly-purified material whose manufacture requires large amounts of energy, toxic solven...

Figure 05. Ask Nature website
(Biomimicry 3.8)

The AskNature.org site was in essence the manifestation of Janine Beynus's vision for a place for engineers, designers and biologists to come together in collaboration. And although the site's audience is growing, the element of collaboration is somewhat lost in the database format (Deldin & Schuknecht, 2014).



Years	Page views	Unique visitors
2008	125,568	22,386
2009	1,066,527	208,661
2010	1,195,928	236,117
2011	1,484,148	295,897
2012	1,790,709	478,486

Source Google analytics

Table 02. Ask Nature usage statistics
(Deldin & Schuknecht, 2014, p. 18)

Design methods: BioTRIZ

Unlike the case study style of the Biomimicry Institute's AskNature database, BioTRZ is a systematic process for determining the optimal transfer of biological inspiration to engineering and design. The BioTRIZ process was created by Julian Vincent when he recognized that there had been no general approach developed for the practice of biomimetics (Vincent, Bogatyreva, Bogatyrev, Bowyer, & Pahl, 2006). The idea for BioTRIZ was born from the Russian strategy TRIZ, roughly translated "Theory of Inventive Problem Solving," developed in the mid 20th century to transfer inventions and solutions from one field of engineering to another (Vincent, Bogatyreva, Bogatyrev, Bowyer, & Pahl, 2006). It works by stripping down a problem to a functional level and then "provides strong indicators towards successful and often highly innovative solutions" (Vincent, Bogatyreva, Bogatyrev, Bowyer, & Pahl, 2006, p. 474).

Stage in TRIZ Process	**Description**
Defining the problem	Ensures a problem is placed in its context and that changing the context is not the most effective solution to the problem at hand
Characterizing the problem (thesis-antithesis)	Opposing or conflicting characteristics are described: typically 'what do I want' v 'what is stopping me from getting it'
Categorizing conflict characteristics	There are 39 contradiction features, one of which is assigned to each characteristic to promote standardization
The contradiction matrix	A contradiction matrix is developed based on existing solutions to similar sets of conflicting characteristics
Matching solutions and problems	The matrix is used as a look-up table for ready made conceptual solutions

Table 03. BioTRIZ stages
Based on content from (Vincent, Bogatyreva, Bogatyrev, Bowyer, & Pahl, 2006)

Vincent acknowledges that there are several other scholars and professionals developing systems for searching biological and ecological literature to uncover functional analogies; however, he also suggests that "a simple and direct replica of the biological prototype is rarely successful…some form or procedure of *interpretation* or *translation* from biology to technology is required" (Vincent, Bogatyreva, Bogatyrev, Bowyer, & Pahl, 2006, p. 475). After reviewing 500 biological phenomena and 270 functions at three levels of hierarchy, BioTRIZ emerged to suggest 2500 conflicts and their resolutions (Vincent, Bogatyreva, Bogatyrev, Bowyer, & Pahl, 2006). Vincent asserts that TRIZ is among the most promising processes for thinking about and applying biomimetic lessons to the designed world, but also recognizes its shortcomings:

> Despite the fact that TRIZ is the most promising system for biomimetics, we still have a mismatch. This is conflated by a number of factors that are currently not normally observed in a technical system. For instance, the more closely an artificial system is modeled on a living prototype, which is typically complex and hierarchical, the more frequently we have emergent effects, which are unpredictable, therefore mostly unexpected and often harmful. Furthermore, one of the basic features of living systems is the appearance of autonomy or independence of action, with a degree of unexpectedness directly related to the complexity of the living system (Vincent, Bogatyreva, Bogatyrev, Bowyer, & Pahl, 2006, p. 476).

BioTRIZ was the response of an engineer to the problem of translating lessons learned between disciplines for the purpose of applied biomimicry. The Living Building Challenge could be seen as the equivalent for architects.

Assessment: Living Building Challenge

The Living Future Institute's Living Building Challenge is a green building certification program in the vein of the better-known US Green Building Council's Leadership in Energy & Environmental Design (LEED) certification. The Living Building Challenge, however, measures success against existing ecological limits rather than efficiency goals aiming to be 'less bad.' Although the Challenge strives for net zero buildings that exist in within the ecological limits of the site ("Living Certification"), there are two other tiers of certification that are less stringent: "Petal Certification" and "Net Zero Energy Building Certification" (International Living Future Institute, 2012). Though the information available is thorough and accessible, there have only been a handful of certified projects: Four Living Certifications, Four Petal Certifications, and Five Net Zero Energy Building Certifications (International Living Future Institute, 2013).

From the history of bionics to biomimetic methods of assessment, the principles of biomimicry as found in the literature lay the foundation for process of analogous analysis. However, it is within the photovoltaic literature that specific problems and historic solutions are found. In the next section of this chapter, the current state of photovoltaic technologies will be laid out and ready to be analyzed using the biomimetic lens.

3.2 Photovoltaic literature

My review of photovoltaic literature begins with a review of the history of the relationship between civilized society and solar energy generally. Throughout the biomimetic literature, many authors speak of or allude to the fact that the first biomimetics were actually those who lived before the perception of a divide between human and nonhuman nature was a widely accepted view. Given this fact, this review will begin with some of the first city-scale civilizations, examining how their thoughts around solar energy technology have evolved into the current condition of solar design philosophy.

3.2.1 Philosophy of solar energy technology

Many ancient civilizations relied solely on knowing the properties of solar energy and its interaction with the built environment to run their cities and find comfort in their home. In the early years of ancient Greece, most homes were heated with fires made from harvested timber from surrounding forests. However, according to the writings of a noted naturalist of the times, Theophrastus, "almost every citizen believed that the sun provides the life-sustaining heat in animals and plants. It also probably supplies the heat of earthly flames. No doubt many people believe they are catching sun rays when making a fire" (Perlin & Butti, A Golden Thread: 2500 years of solar architecture and technology, 1980, p. 3). The renewability of timber, however, was limited. And just as the impending resource scarcity we are being faced with today has driven us to seek renewable energy sources including solar, 2,500 years ago the Greeks began orienting their homes to take advantage of the sun's energy in response to a dire shortage of timber due to its overuse as a fuel for heating homes (Perlin & Butti, A Golden Thread: 2500 years of solar architecture and technology, 1980).The timber shortage was so critical and widespread, that entire city-sized settlements were planned using principles of solar geometry and elementary thermodynamics. At the building scale, homes were designed to allow the sun to enter the homes in the winter when it was low in the sky and the earthen floors and adobe walls absorbed and retained the heat (Perlin & Butti, A Golden Thread: 2500 years of solar architecture and technology, 1980). At the city-scale, streets were laid out in grids to allow every home access to southern exposure supporting equity in their democratic society demonstrating that "solar architecture cut across class lines…rich and poor city dwellers as well as princes and kings relied on sun" (Perlin & Butti, A Golden Thread: 2500 years of solar architecture and technology, 1980, p. 6).

The Romans faced similar timber shortages resulting from residential conditioning along with shipbuilding, city construction, and luxuries such as heating public baths (which could consume up to 280 pounds of wood an hour) (Perlin & Butti, A Golden Thread: 2500 years of solar architecture and technology, 1980). And, although in Rome the benefits of advanced solar design technologies favored the wealthy over the less fortunate more so than in democratic Greece, sun-right guarantees were incorporated into the Justinian Code of Law in the sixth century A.D. stating: "*If any object is so placed as to take away the sunshine from a* heliocaminus, *it must be affirmed that this object creates a shadow in a place where sunshine is an absolute necessity. Thus it is in violation of the* heliocminus' *right to the sun*" (Perlin & Butti, A Golden Thread: 2500 years of solar architecture and technology, 1980, p. 27). It is clear that in these ancient civilizations the ability to harness the sun's energy should be accessible to all. Similar solar design principles were being applied further east in China and Japan as well.

In the origins of the industrial revolution, as more families and individuals began dwelling in urban areas and the widespread use of fossil fuels became more common, knowledge of solar energy became increasingly less important and the consequences of ignoring solar principles became dire. As the poor began to migrate into the cities, they were forced to live in crowded and sunless conditions, which physicians later linked with widespread epidemics (Perlin & Butti, A Golden Thread: 2500 years of solar architecture and technology, 1980). In response many countries adopted public health and town planning laws to ensure sun-rights for all citizens (Perlin & Butti, A Golden Thread: 2500 years of solar architecture and technology, 1980). Though this helped curb the visible symptoms of sun-deprived classes, because it was not able to remarry energy consumption and solar energy in the way that many ancient civilizations had, there are very few cases in which the underlying cause of the problem was cured.

Almost immediately after the beginning of the industrial revolution and the universal use of coal as the primary source of electricity in the nineteenth century, a handful of scientists from across industrialized nations began voicing their concerns with the widespread use of coal. One voice against coal was the Swedish-American engineer, John Ericsson. Ericsson was both concerned and hopeful that "solar power [could] offer the only way to avert an eventual global economic paralysis that would result in putting 'a stop to human progress'" (Perlin, From Space to Earth: The Story of Solar Electricity, 1999, p. 4). Throughout the developed world, scientists and engineers worked toward a technological solution to capture this invaluable energy to be transformed into a usable form. In France, Augustine Mouchot believed that the sun's heat could replace the use of coal in Europe altogether and dedicated his life's work to experimenting with all kinds of solar technology (Perlin, From Space to Earth: The Story of Solar Electricity, 1999). By the 1870s, he and other solar science engineers had convinced many that solar energy could produce "unlimited power at almost no cost" (Perlin, From Space to Earth: The Story of Solar Electricity, 1999, p. 5). However, as research continued it became clear that although the sun as a resource had no cost, the technology/materials needed to transform that light into usable energy was consistently the limiting factor to the success of solar technologies, particularly photovoltaics.

Throughout the 19th century and into the beginning of the 20th, the idea of solar energy technology remained broad including studies of passive strategies for trapping heat behind using glass, powering machinery with sun motors, mirrors to focus light to run a generator, and passive solar thermal systems among others. Cost remained the prominent factor limiting the momentum of solar energy, as fossil fuels remained cheap for the first 50 years of their widespread use. The only viable applications were those that could not possibly be connected to the existing grid: small rural installations and space. Space program funding kept the photovoltaic dream alive and supported to research without which PV technology would not have advanced nearly as far as it has (Perlin, From Space to Earth: The Story of Solar Electricity, 1999).

Then in 1973 photovoltaics returned to earth. The OPEC embargo served as a reminder of the instability of the fossil fuel resources that modern industrialized society had become so reliant on. Oil prices increased by an incredible 25 times between 1970 and 1980 (Perlin, From Space to Earth: The Story of Solar Electricity, 1999). During this time, solar energy picked up momentum once again. This time the focus was narrowed to technologies that could convert solar energy into usable electricity, and scientists like Martin Real put the phenomenon of photovoltaics, which had been discovered over a century before, into action (Perlin, From Space to Earth: The Story of Solar Electricity, 1999). In 1977 Science Magazine wrote: "if there is a dream solar technology it is photovoltaics – solar cells… a space-age electronic marvel at once the most sophisticated technology and the simplest, most environmentally benign source of electricity" (Perlin, From Space to Earth: The Story of Solar Electricity, 1999, p. 11). With this narrowed focus on photovoltaics, solar energy engineers were able to address the persistent problems associated with cost through countless PV design iterations – varying production processes, light-capturing materials, constructions, and applications.

The developed world's reliance on electricity drove the narrowing of solar energy engineers' focus to photovoltaics specifically. Passive strategies that have been proven successful since the times of the Greeks would no longer suffice as solutions to the energy needs of society. And, although those strategies have not been completely lost, they have been greatly underutilized since the focus was shifted to the promise of photovoltaics.

In the developing world, however, photovoltaics became an important tool for distributing electricity that had benefited the developed world for decades, in turn promoting equity. The opportunities for promoting equity through utilizing photovoltaics range from extending phone lines to the most rural areas of the US to powering drills to dig wells in Sub-Saharan Africa to delivering affordable electricity to the unelectrified from a reliable and indigenous source (Perlin, From Space to Earth: The Story of Solar Electricity, 1999).

Most recently, the focus of photovoltaic applications has been on improving efficiency to the extent that PVs can support the increasing energy demand associated with personal electronics, home entertainment, and conditioning services.

3.2.2 History of photovoltaic technology

The origins of photovoltaic discovery date back to 1839 when French physicist Edmond Becquerel "succeeded to observe the battery voltage increase due to the light illumination on silver plates" (Bahrami, Mohammadnejad, & Soleimaninezhad, 2013, p. 163). Then in 1860 Willoughby Smith, chief electrician managing the telecommunication network installation, made the groundbreaking discovery that led solar technology toward the photovoltaics that we know today. While working on the trans-Atlantic telegraph cable project, Smith invented a device made of crystalline selenium to detect flaws in cables that were submerged and realized it was affected by light (Perlin, From Space to Earth: The Story of Solar Electricity, 1999). In the following decade, William Grylls Adams, a professor from Britain, continued to explore the properties of selenium and its potential to contribute to the development of solar technology. Then, in late 1870 Charles Fritts constructed the first photovoltaic module by spreading a thin layer of selenium onto a metal plate and covering it with thin semi-transparent gold-leaf film (Perlin, From Space to Earth: The Story of Solar Electricity, 1999). Further iterations were developed throughout the next 30 years. Then in 1905, amidst the excitement for photoelectric technology, Albert Einstein published a paper demonstrating that light actually contained small packets of energy, which were later, named *photons* (Perlin, From Space to Earth: The Story of Solar Electricity, 1999). This laid the foundation for the great strides in photoelectric research that were taken in the twentieth century.

The first generation of current conventional crystalline silicon photovoltaic cells was developed in the early 1950s at Bell Laboratories. Bell scientists Calvin Fuller and Gerald Pearson were responsible for a string of improvements to past iterations of photovoltaic cells, and were affectionately called "the experimentalist's experimentalist" (Perlin, From Space to Earth: The Story of Solar Electricity, 1999, p. 25). Their contributions included controlling the introduction of impurities to the silicon necessary to improve conducting properties – the addition of gallium made it positively charged and then dipping it into a hot lithium bath created a negative charge. Where the positive and negatively charged silicon meet there is a permanent electric force (the p-n junction), which allows charge to flow and electricity to be produced (Perlin, From Space to Earth: The Story of Solar Electricity, 1999). With the technology of the photovoltaic cell on its way to functional, another Bell scientist, Darryl Chapin, worked on the feasibility of utilizing the charge that is produced as electricity outside the laboratory.

Today's photovoltaic technologies have experienced several advances since Chapin, but conventional silicon PV technology is still quite reminiscent of early photovoltaics. The motivations and barriers of Chapin are even more similar than the technology:

> The main motivation for developing solar energy is the desire to get away from fossil fuels with their adverse effect on the environment. At the [2000] growth rate it will take us far into the second half of the next century to get a relevant contribution by PV to world energy demand. The major reason for the low penetration of PV today is the high cost (Goetzberger & Hebling, Photovoltaic materials, past, present, future, 2000, p. 2).

3.2.3 Conventional crystalline silicon photovoltaics

This section will summarize the status of current technologies involved in the complete lifecycle of conventional crystalline silicon photovoltaics. It will also identify the existing environmental, health and safety, and economic barriers to sustainability from all phases from material extraction and refining to manufacturing process to installation and applications to end-of-life management.

3.2.3.1 Lifecycle of conventional PVs

Crystalline silicon accounts for over 90% of the PV market (Compaan, 2006). Since the mid-twentieth century, crystalline silicon solar cells have had significant efficiencies of over 10%

(Bahrami, Mohammadnejad, & Soleimaninezhad, 2013). Although, from an objective physics perspective, it is known that this traditional material (silicon) is not the ideal material for photovoltaic conversion, the PV market has embraced it because the technology had already been highly refined by the semiconductor market (Goetzberger & Hebling, Photovoltaic materials, past, present, future, 2000).

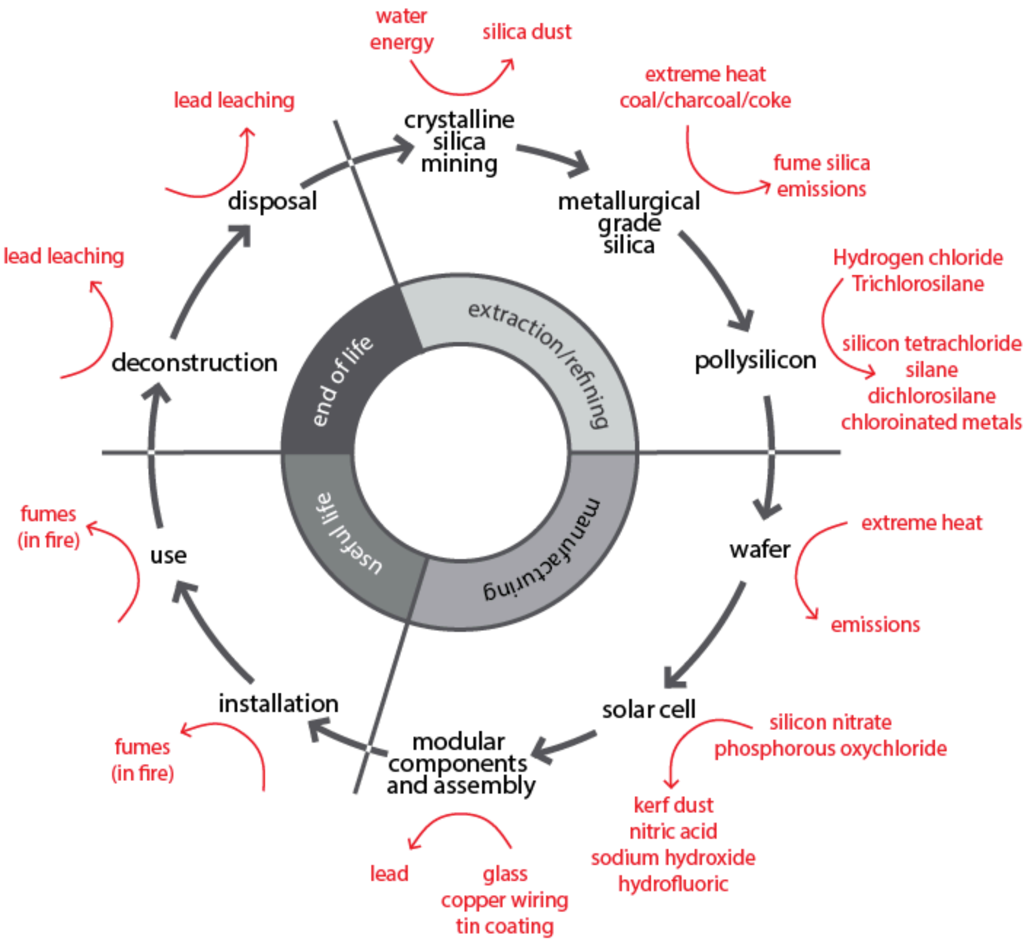


Figure 06. Lifecycle impacts of conventional crystalline silicon photovoltaics
Developed by author

Material extraction and refinement processes

The original crystalline silicon PV uses single-crystal silicon. Crystal silicon is produced by refining raw quartz or silica sand, which is mined using methods well established by the glass production industry (Stoppato, 2008). The extraction of silica sand can result in the release of silica dust, which can be harmful to mining workers; however, there have been stringent health and safety measures put into place to reduce risks (Good Company, Unknown). As with almost any mining, the associated earth moving, crushing, milling, and washing there is also a great deal of ecosystem disruption on site.

Once silica sand is extracted, it must go through an extremely energy-intensive and costly refinement process. The silica sand is mechanically pulverized and then fused with a carbon compound – often coal or coke – under extreme heat in an electric arc furnace (Good Company, Unknown) (Stoppato, 2008). The resulting product is metallurgical silicon, which is approximately 98% pure silicon. However, 98% pure is still not pure enough for photovoltaic cells (Stoppato, 2008). Next, the metallurgical silicon is pulverized and combined with hydrogen chloride gas and copper catalyst resulting in trichlorosilane. The trichlorosilane is then distilled until the required purity is achieved and polysilicon is produced through the deposition of chemical vapor (Stoppato, 2008).

In many cases, photovoltaic manufacturers buy silicon materials that were rejected by the semiconductor market for not meeting purity requirements (Goetzberger & Hebling, Photovoltaic materials, past, present, future, 2000). In these instances, the lifecycle of the crystalline silicon photovoltaic begins with the manufacturing of silicon wafers from the rejected materials.

Manufacturing processes

Crystalline silicon is applied in photovoltaic technologies in the form of wafers, which are most often cut from a large boule grown using the traditional Czochralski method. The Czochralski method involves melting down polysilicon at 1500 degrees Celsius, dipping a seed into the molten silicon, and letting a boule form around it (Miles, 2006). Crystalline silicon rods are cut into .2-.5mm wafers for use in solar cells; this is a costly process that requires diamond-cutting tools and can result in the loss of up to 50% of the materials throughout the sawing process (Goetzberger & Hebling, Photovoltaic materials, past, present, future, 2000). The wafers are then mechanically polished to remove damage from the sawing process and chemically polished to remove damage from the mechanical polishing process (Miles, 2006). Next surface etching is performed to "minimize reflection losses and to increase the angles at which light rays are refracted into the silicon (to enhance the optical path length)" (Miles, 2006, p. 1093).

One lower-impact alternative to single crystal silicon is multicrystalline silicon. Multicrystalline silicon has begun to infiltrate the PV market already, and its presence is constantly growing. In 2006 "over 60% of the module production is now based on the use of multicrystalline silicon wafers rather than those produced using the Czochralski method" (Miles, 2006, p. 1093). In the production of multicrystalline silicon PV cells, molten silicon is poured into molds and hydrogen is incorporated (Miles, 2006). There are significant cost and efficiency advantages to using multicrystalline silicon over singe crystal silicon. Economically, multicrystalline silicon costs only 80% of typical single crystal silicon, incurs lower capital costs and is much less sensitive to the quality of the silicon feedstock used. Although the efficiency of multicrystalline silicon cells are approximately 2-3% lower than that of single crystal silicon, the resulting square or rectangular shape of each cell allows for higher packing density of cells resulting in higher efficiencies of full panels (Miles, 2006). After the cells are created, they are put together into the full photovoltaic panel. This involves the addition of glass and copper.

Technology and efficiency

In essence, the mechanics of the photovoltaic process as seen in current conventional silicon PVs involves a pocket of energy from the sun, or a 'photon,' striking a negatively charged doped silicon surface, driving the migration of the free electron to a "hole" in the molecular structure of positively charged doped silicon resulting in the creation of an electric current (Mertens, 2013). The mechanics of the photovoltaic process will be laid out in further detail in the "Mechanics of Photovoltaics" chapter.

Transportation, installation and use

Following the manufacture of photovoltaics, the final product is transported, installed and functions throughout the rest of its lifetime. Although the environmental impacts of transporting raw materials is typically included in lifecycle analyses, the impacts of transportation of manufactured modules is not always included nor explicitly discussed in the lifecycle analysis literature.

Conventional silicon photovoltaic cells have been used in a wide variety of applications from powering small electronic devices to simple arrays to distributed generation on buildings to utility-scale generation feeding directly into the grid. Throughout the world conventional PV arrays have been installed on rooftops as a means of reaching the goal of greater contributions of renewable energy to the larger energy production and distribution system. Distributed generation initiatives in the 1990s included Germany's thousand roofs program, the Japanese Ministry of International Trade and Industry's 70,000 roof program, and the US million roof program under President Bill Clinton (Jackson & Oliver, 2000). Conventional PVs have also been installed and operated in utility-scale centralized grid-connected systems; however, this thesis focuses on distributed generation as it is a strategy that better mimics the distributed energy generation by plants in an ecosystem therefore better fitting the biomimetic theme.

Regardless of application, trained installers are required to ensure safe and effective installation. Due to the numerous potential hazards associated with the installation of photovoltaics, strict Occupational Safety and Health Administration (OSHA) standards have been put in place to protect installers (Solar Energy International, 2007). The promise of photovoltaics is often associated with the fact that PVs can continue provide usable electricity without continuous inputs (like in fossil fuel based systems). However, trained professionals are also required to ensure sustained functioning by providing maintenance and repair.

Manufacturing waste and end-of-life management

The perception that photovoltaics can operate without continuous inputs also suggests that there is little to no waste associated with energy production; however, there are two major waste streams that come from the life of the photovoltaic. There is already infrastructure in

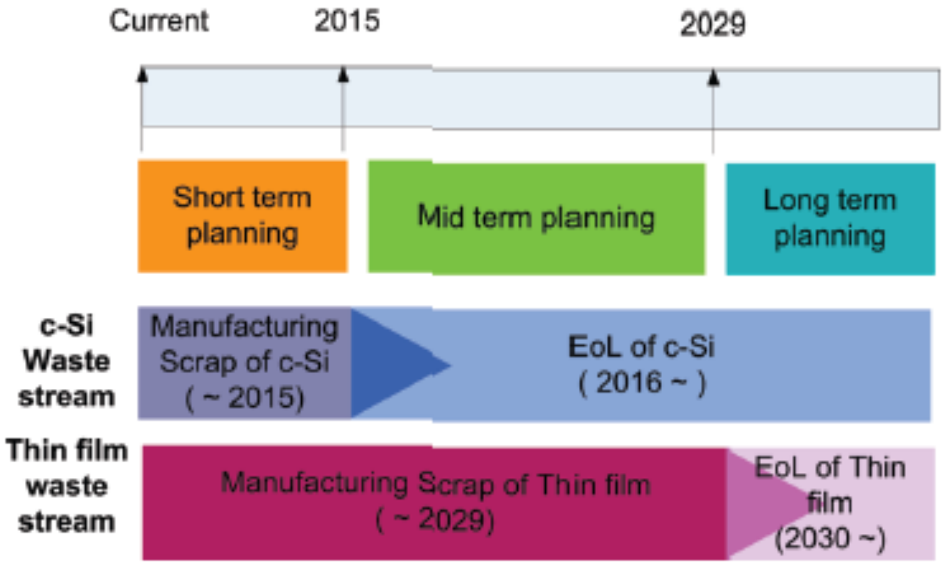


Figure 07. Timeline for recycling PV materials at all life stages
(Choi & Fthenakis, 2010, p. 8679)

place supporting the recycling of the first: manufacturing scraps. The other, end-of-life waste, presents a more complicated problem since the expected lifetime of a conventional PV is 25-30 years, and as a result the demand for end-of-life recycling services has been low thus far (Choi & Fthenakis, 2010) (McDonald & Pearce, 2010). There are several scholars who have written on the potential for expanding PV recycling programs that already exist and developing the components that have yet to be designed.

Jun-Ki Choi and Vasilis Fthenakis have conducted several studies aimed at quantifying the economic and environmental feasibility of developing a PV recycling infrastructure for short-, mid-, and long-term PV waste. The planning of a larger PV recycling infrastructure that can accommodate both types of waste has started with the study of similar industries' approaches to recycling including electronics, batteries, and even carpet (Choi & Fthenakis, 2010). In the case of PV recycling, Choi and Fthenakis have concluded the majority of negative environmental impacts are associated with transportation, and therefore their feasibility studies have been focused on optimizing the location of the recycling center site (Choi & Fthenakis, 2010). This is a particularly difficult problem given that, generally, "the regions where major PV manufacturers are sited are different than locations of major installations of PV systems" (Choi & Fthenakis, 2010, p. 8678).

Other scholars have focused on smaller scale process-level PV recycling issues – what happens inside this large PV recycling infrastructure. N.C. McDonald and Vasilis Fthenakis both write on feasibility of recycling process. Generally the process for recycling monocrystalline silicon PVs involves removing the glass, removing the silicon wafers, and removing the layer of lamination using a process that requires temperatures up to 500 degrees Celsius (McDonald & Pearce, 2010). Though the International Panel on Climate Change (IPCC) reports that PV recycling for concentrated and large-scale is economically viable, that may not be the case for distributed PV installations (International Panel on Climate Change). It In a study conducted by N.C. McDonald, it was found that the economic profit associated with re-selling the materials (semiconductor and glass) found in conventional crystalline silicon PVs was less than the cost to recycle them (McDonald & Pearce, 2010). This can, however, change depending on whether manufacturing responsibility legislation is in place to account for the costs associated with taking up landfill space. Though there is no economic motivation for pursuing silicon-based PV recycling, the presence of toxic substances used in PV technology does suggest a need to regulate their decommissioning (McDonald & Pearce, 2010). The health and safety and environmental impacts of the disposal of silicon PVs will be discussed in the following section.

3.2.3.2 Economic, social, and environmental barriers to sustainability

If the hope of photovoltaics is to produce affordable energy that eliminates harmful environmental impacts and ensures equal access to clean energy, then there are a number of shortcomings that need to be addressed before PV can be deemed a sustainable method for producing energy – sustainability as measured against nature.

Economic impacts

As seen throughout the review of current technologies there are six major areas in which these technologies can fall short of the aforementioned measures of success: cost, material acquisition, production processes, efficiency of cells, stability of cells outside the laboratory, and end-of-life management.

Since the early 1900s, solar energy engineers have recognized that cost is consistently the limiting factor when it comes to the viability of solar energy as a primary source of electricity (Perlin, From Space to Earth: The Story of Solar Electricity, 1999). Because the raw material needed to create crystalline silicon photovoltaic cells, quartz silicon sand, is the same material used by the glass industry, material extraction is reasonably priced (Good Company, Unknown). In fact, nearly 50% of the total cost of a PV module from raw material to end-of-life management is in the production of processed silicon wafers (Goetzberger & Hebling, Photovoltaic materials, past, present, future, 2000). The energy needed to purify silicon, melt it down to be formed into a boule, and the precise tools needed to cut the boule into wafers are all aspects of the manufacturing process that contribute to the high cost of photovoltaics.

There have been a number of technological solutions tested to reduce this cost in the production process. One strategy involves changing the source of the necessary material using rejected materials from the semiconductor market instead of creating crystalline silicon from scratch. This strategy has been limitedly effective since the semiconductor market and the photovoltaic market have not grown at the same rate and the volatility of the semiconductor market has made supply difficult to predict (Goetzberger & Hebling, Photovoltaic materials, past, present, future, 2000). Another approach involves changing the form of the product from wafers to thin film, "to reduce cost by eliminating the costly sawing and crystal growing process and at the same time minimize the amount of silicon per area" (Goetzberger & Hebling, Photovoltaic materials, past, present, future, 2000, p. 10). There are yet other strategies that approach reducing economic burden by increasing efficiency – the more electricity that is produced the faster the return on investment.

There have been many strategies that have been developed, tested, and in some cases widely adopted to reduce the actual cost of producing photovoltaic cells. However, there are energy- and cost-intensive parts of the process that could not be altered or avoided. In response to this, municipal, state, and federal governments have developed a variety of incentive programs to reduce the financial burden solar energy has on the consumer.

Social impacts

There are a number of processes, necessary chemical inputs, and unintended outputs that potentially pose threat to the health or safety of the employees manufacturing PVs or the surrounding communities. Some of the negative effects on the health and safety of individuals and communities are inevitable given the standard processes; others are contingent on exceptional circumstances such as spills, facility fire, or other accident. Although many of the health and safety issues brought up in this section do not regularly affect the workers and communities around manufacturing plants, it is important to identify the risks to better understand why current conventional PVs are not yet an environmentally *sustainable* alternative. In non-human nature, the materials needed to carry out the process of photosynthesis are made without extreme temperatures and inorganic, hazardous materials. PV manufactures and recyclers have addressed these issues by conforming to strict safety codes. As a result there has never been a significant incident of health or safety impairment in United States facilities (Good Company, Unknown).

	Process	**Additional Inputs**	**Unwanted outputs**	**Potential health/safety Impacts to workers and/or communities**
Raw material extraction and refining	Crystalline silica mining	Water	Release of silica dust	Silicosis: scar tissue in the lungs, reduces the ability to breathe
		Energy		Chronic obstructive pulmonary disease
				Rheumatoid arthritis
				Scleroderma
				Sjogern’s syndrome
				Lupus
				Renal disease
	Upgrading silica sand to metallurgical grade sand (for metal alloys)	Extreme heat	CO2 and SO2 emissions (intensity varies by region)	Long term effects of air pollution
		Coal, charcoal, or coke	Fume silica	Silicosis: scar tissue in the lungs, reduces the ability to breathe
				Chronic obstructive pulmonary disease
				Rheumatoid arthritis
				Scleroderma
				Sjogern’s syndrome
				Lupus
				Renal disease
	Upgrading metallurgical grade silicon to polysilicon	Hydrogen chloride gas	Silicon tetrachloride	Can cause skin burns Eye irritant Respiratory irritant (has been dumped in waterways in China)
		Trichlorosilane	Silane	Reacts explosively with water
			Dichlorosilane	
			Chlorinated metals	Unknown
Manufacture	Growing the silicon crystal boule	Extreme heat	CO2 and SO2 emissions	Long term effects of air pollution
	From polysilicon ingot to wafer to cell	Diamond-cutting tools	Kerf dust (when sawing)	Respiratory irritant Chemical burns Flammable (reflective coating)
		Extreme heat	Nitric acid (etching)	
		Phosphorous oxychloride	Sodium hydroxide (etching)	
		Silicon nitrate (reflective coating)	Hydrofluoric acid (etching)	
	Module components and assembly	Glass	Lead in solder materials	Unknown
		Copper wire		
		Tin coating		
Installation and use	Installation	Transportation fuel	Fumes (in event of fire)	Hazardous fumes Physical harm
			On-site accidents (falls, etc.)	
	Use	None	Electric shock (in event of fire)	Unknown
End-of-life management	Decommissioning	None	Lead leaching (if not properly disposed of)	Contaminate soil and/or water bodies
	Disposal	Transportation fuel		

Table 04. Negative social impacts of photovoltaics
Based on content from (Good Company, Unknown)

Other social barriers to the wide adoption of photovoltaics are threatening to culture rather than to the health and well being of people. As reported by the International Panel on Climate Change:

> Visual concerns…exist for distributed solar systems in built-up areas, which may find greater resistance for applications on historical or cultural buildings versus modern construction. By avoiding conservation areas and incorporating solar technologies into building design, these conflicts can be minimized (International Panel on Climate Change, p. 372).

Another important social barrier to the wide adoption of the photovoltaics is closely tied to the economic barriers – navigating the complicated subsidy structures in place to counter high PV costs (International Panel on Climate Change).

Environmental impacts

Though several studies, have demonstrated the greatly *reduced* environmental impact of renewable energy in comparison to conventional fossil fuels, negative environmental impact does still exist with PVs technologies. Similar to health and safety considerations, there are many protocols in place to ensure limited environmental impact of the material extraction, manufacturing, use and disposal of conventional silicon PVs (Good Company, Unknown) (International Panel on Climate Change). However, there are instances throughout the lifecycle of the conventional PVs that pose a threat to the environment. See Table 05 on the following page for a list of potentially harmful environmental impacts.

	Process	Additional Inputs	Unwanted outputs	Potential environmental impacts
Raw material extraction and refining	Crystalline silica mining	Water	Release of silica dust	Unknown
		Energy		
	Upgrading silica sand to metallurgical grade sand (for metal alloys)	Extreme heat	CO2 and SO2 emissions (intensity varies by region)	Contributes to atmospheric pollution
		Coal, charcoal, or coke	Fume silica	Unknown
	Upgrading metallurgical grade silicon to polysilicon	Hydrogen chloride gas	Silicon tetrachloride	Can cause skin burns Eye irritant Respiratory irritant (has been dumped in waterways in China)
		Trichlorosilane	Silane	Reacts explosively with water
			Dichlorosilane	
			Chlorinated metals	Unknown
Manufacture	Growing the silicon crystal boule	Extreme heat	CO2 and SO2 emissions	Contributes to atmospheric pollution
	From polysilicon ingot to wafer to cell	Diamond-cutting tools	Kerf dust (when sawing)	Respiratory irritant Chemical burns
		Extreme heat	Nitric acid (etching)	
		Phosphorous oxychloride	Sodium hydroxide (etching)	
		Silicon nitrate (reflective coating)	Hydrofluoric acid (etching)	Flammable (reflective coating)
	Module components and assembly	Glass	Lead in solder materials	Unknown
Installation and use	Installation	Transportation fuel	Fumes (in event of fire)	Hazardous fumes
			On-site accidents (falls, etc.)	
	Use		Electric shock (in event of fire)	Unknown
End-of-life management	Decommissioning		Lead leaching (if not properly disposed of)	Contaminate soil and/or water bodies
	Disposal	Transportation fuel		

Table 05. Negative environmental impacts of photovoltaics
Based on content from (Good Company, Unknown)

3.2.4 Emerging technologies

Although conventional crystalline silicon cells still dominate the photovoltaic market, there are several emerging technologies that have addressed the barriers to sustainability of conventional PV systems while maintaining market potential. Some technologies aim to cut back costs, materials, embodied energy, or hazardous waste through altering production processes. Others propose new light-capturing materials that reduce costs, reduce material demand, reduce energy intensity in the production process, and improve the viability of material recycling without compromising efficiency. Others still, propose new applications for existing technology or hybrid applications of emerging material and production technologies. The following describes the most prevalent emerging technologies found in the literature. Strategies are not necessarily mutually exclusive.

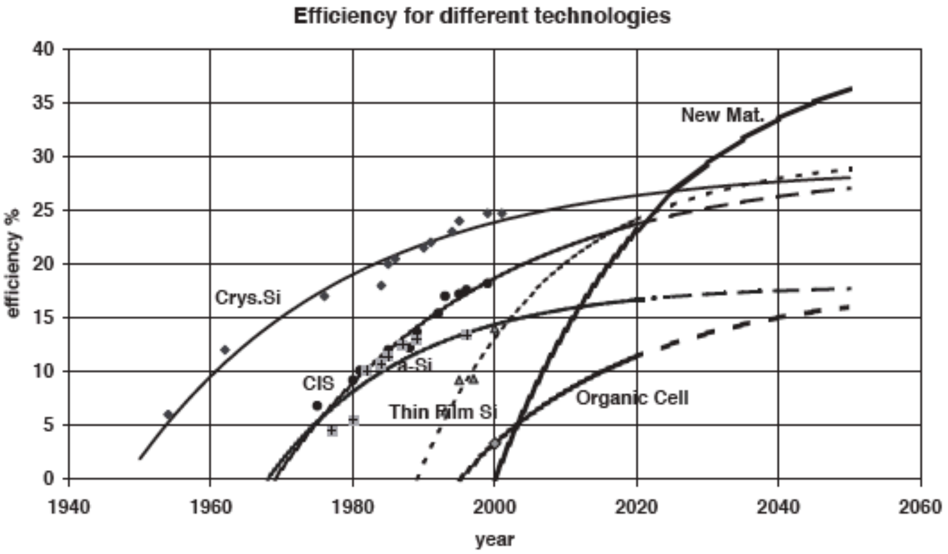


Figure 08. Comparing efficiencies of emerging PV technologies
(Goetzberger, Luther, & Willeke, Solar cells: past, present, future, 2002, p. 10)

3.2.4.1 New production process technology

One approach to addressing the barriers to sustainability of conventional crystalline silicon PVs is altering the production methods without straying from the proven effective material, silicon.

Silicon-based thin film

Emerging thin-film technologies aim to address the cost barriers of conventional systems through new production process that replace costly sawing of crystalline silicon rods with the production of film. “Many observers expect that the thin-film PV materials will soon provide the cost breakthroughs needed to make solar electric power cost competitive with other generation technologies” (Compaan, 2006, p. 2173). Though crystalline silicon film technologies greatly reduce the resource intensity and high economic costs of crystalline silicon wafers, they do still rely on silicon-based, or other toxic materials, as the active element therefore not addressing environmental issues associated with material and end-of-life management. However, this has been acknowledged by those in the field, Compaan stating, “the dream of thin-film PV has been reduction in cost through the use of inexpensive substrate materials and reduction in the amount of (usually expensive) electronically active materials used” (Compaan, 2006, p. 2171).

There are three dominant types of inorganic thin-film technologies that are well on their way to becoming economically viable alternatives to conventional silicon PV systems. The three materials that have been most successful in consistently achieving efficiencies greater than 10% include amorphous silicon (a-Si:H), copper indium gallium diselenide (CIGS), and CdTe (Compaan, 2006) (Miles, 2006). This section will cover amorphous silicon, and other thin-film techniques will be discussed in the following section. “Thin films of amorphous silicon are usually produced using the PECVD of gases containing silane (SiH4) or using hot wire CVD” (Miles, 2006, p. 1094). In production, high levels of hydrogen (~10%) are established within the amorphous silicon film, which greatly improves the electronic properties as compared to pure amorphous silicon, but are still not as great as crystalline silicon (Green, 2003). There are several types of hydrogenated amorphous silicon solar cells that have proved to be effective, including amorphous silicon carbide (aSiC), amorphous silicon geranium (a-SiGe), microcrystalline silicon (uc-Si), and amorphous silicon nitrate (a-SiN). However, the thin-film material with the highest stability reported is polymorphous silicon (pm-Si:H) with a high concentration of hydrogen (Bahrami, Mohammadnejad, & Soleimaninezhad, 2013).

The potential for thin-film PV strategies to become competitive with conventional silicon cells is because thin-films “have direct energy band gaps and consequently high optical absorption coefficients, resulting in the need for only a few microns of materials to absorb all the incoming light” (Miles, 2006, p. 1092). Additionally, amorphous silicon thin film uses a p-i-n structure rather than just p-n as in other silicon PVs – “by inserting a lightly doped ‘intrinsic’ layer between p and n-type regions, the high electric field region arising from the work function difference between these regions can be stretched over a large volume" (Green, 2003, p. 188). However, the answer to the question of sustainability of photovoltaic technology may not lie in silicon technologies.

3.2.4.2 Emerging material technologies

Others have approached photovoltaic technology development through the use of new materials entirely. Though experimenting with new materials has often resulted in lower efficiencies than the well-established crystalline silicon cells, there is potential for these new photovoltaic materials to transform the industry.

New inorganic thin-film technologies

There are several other materials aside from silicon being used to create thin-film solar cells. These cells obtain the same lower cost production benefits as amorphous silicon thin-film cells over conventional crystalline silicon cells, however, these chalcogenide cells also result in higher efficiencies due to the nature of the alternative materials. As a result, they are often used for cheap mass productions (Bahrami, Mohammadnejad, & Soleimaninezhad, 2013).

The three most common materials used in the production of these cells are cadium selenium (CdS), copper indium diselenide (CIS) and cadium telluride (CdTe). All three have seen efficiencies over 17% (Bahrami, Mohammadnejad, & Soleimaninezhad, 2013). The most popular process for manufacturing chalcogenide thin-film cells involves methods of physical vapor deposition (PVD), however there are other less popular methods that do not require vacuum conditions. These other methods include printing, spraying, and electrochemical deposition and they allow more cells to be produced more quickly at a lower price (Bahrami, Mohammadnejad, & Soleimaninezhad, 2013). Copper indium gallium diselenide (CIGS) is made by co-evaporation of the elements in a high vacuum chamber or by selenisation or sulphidisation of pre-deposited elemental precursor layers (Miles, 2006).

Even though there is promise in these new thin-film technologies, there are also some concerns. One is the toxicity of the materials involved. CdTe hasn't been widely accepted in the market because its base is a toxic material (Green, 2003). The instability of the efficiencies of the material is also an issue. All three also lose efficiency with exposure to the sun (Green, 2003).

Dye-sensitized cells (organic/inorganic hybrid)

According to Bahrami, "dye-sensitized solar cells are of the most important groups of new generation cells…these cells behave in a different way from the other types of solar cells and their process is almost analogous to that of photosynthesis" (Bahrami, Mohammadnejad, & Soleimaninezhad, 2013, p. 177). Dye-sensitized solar cells (DSSCs) can be made with organic or inorganic semiconductors, but the way in which the dye enhances the photovoltaic process is the same:

> "In these cells, dye molecules absorb the incident light as chlorophyll in plants and produce negative and positive carriers. By comparing to the other solar cells based on solid semiconductors, dye-sensitized solar cells are the chemical photoelectric systems" (Bahrami, Mohammadnejad, & Soleimaninezhad, 2013, p. 177).

Though the processes may utilize the same strategies as natural systems, the material and structural elements of dye-sensitized solar cells (DSSCs) do not. The materials used in DSSCs include protective glass, semiconductor electrolyte and some type of dye, commonly iodide (Chaar, lamont, & Zein, 2011). The environmental impact of each of these material inputs varies greatly as there are many different types of DSSC technology being developed. However, due to the easier and lower cost fabrication processes, DSSCs often offer comparable or higher efficiencies than amorphous silicon cells at a much lower cost (Bahrami, Mohammadnejad, & Soleimaninezhad, 2013) (Razykov, Ferekides, Morel, Stefanakos, Ullal, & Upadhyaya, 2011). Conversion efficiencies for DSSCs can be up to 7-11% (Goetzberger, Luther, & Willeke, Solar cells: past, present, future, 2002). Some DSSC systems incorporate organic materials, which can be preferable to inorganics from a waste-management point of view, but not necessarily from an economic point of view as resulting efficiencies are often lower.

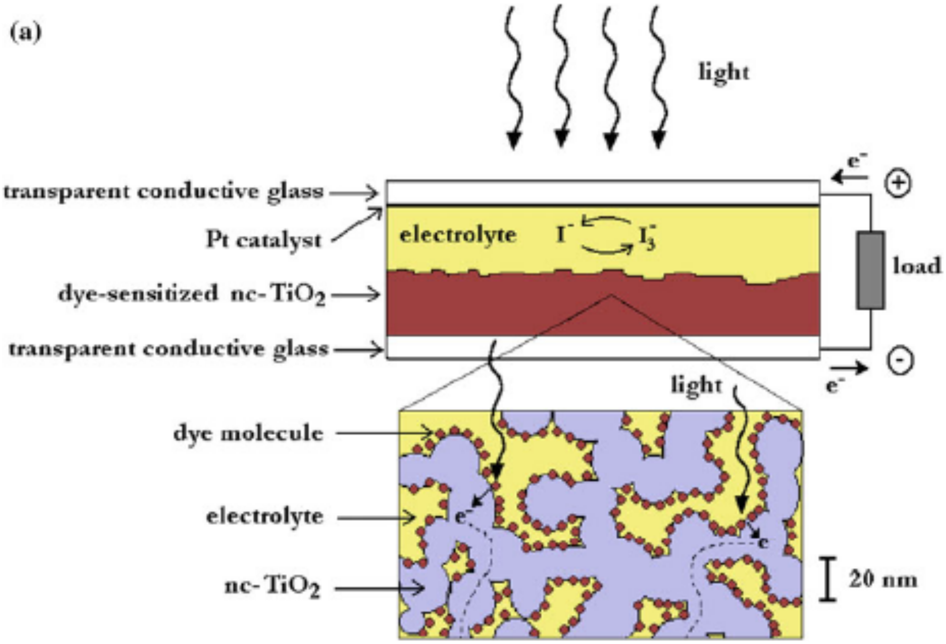


Figure 09. Structure of the dye sensitized solar cell
(Bahrami, Mohammadnejad, & Soleimaninezhad, 2013, p. 178)

Though the cost effectiveness of DSSCs and their ability to mimic photosynthetic processes more accurately than any other current technology make them an attractive option, there are still barriers to overcome before DSSCs can be deemed a "sustainable" option for solar energy production. Many DSSCs experience problems with stability over time and temperature range issues (Goetzberger, Luther, & Willeke, Solar cells: past, present, future, 2002). There are also environmental concerns:

> [Many DSSCs} contain volatile solvents in their electrolytes that can permeate across plastic (i.e. organic compounds) and also present problems for sealing the cells. Cells that contain these solvents are therefore unattractive for outdoor use due to potential environmental hazards. Researchers have developed solar cells that use solvent-free electrolytes, but the cell efficiencies are too low (Chaar, lamont, & Zein, 2011, p. 2171).

Organic cells

Organic photovoltaics (OPVs) integrate the early 19th century discovery of photoconductivity in organic material anthracene with current trends in photovoltaics. Organic solar cells offer some benefit in terms of cost and material use, but fall quite short of current conventional photovoltaics in terms of efficiency. In the material literature, it is widely recognized that the production process and associated costs of organic solar cells are much less than costs associated with current conventional silicon solar cells – only about one third of the cost (Zhu, Wei, Wang, & Wu, 2009) (Spanggaard & Krebs, 2004). In addition to low cost production methods, "extremely high optical absorption coefficients are possible with these materials, which offers the possibility for the production of very thin solar cells (far below a um) and therefore only very small amounts of needed materials" (Goetzberger, Luther, & Willeke, Solar cells: past, present, future, 2002, p. 8). The thin and transparent properties allow OPVs to offer a wider variety of potential applications than rigid conventional PV modules such as integration into fabrics, clothing, large-area coatings, glazing and more.

The materials that make up organic solar cells often consist of three main functional parts plus a protective layer of glass or flexible plastic. The three functional pieces include two electrode layers with the organic light-absorbing layer sandwiched between the two. The top electrode layer must be transparent, and is often made of indium-tin-oxide (ITO) (Spanggaard & Krebs, 2004). Unlike in inorganic photovoltaics, the intermolecular forces at play in organic semiconductors are not strong enough to form 3D crystal lattices, preventing the formation of a conduction and valance band - allowing for flexibility, but consequently significantly limiting the efficiency of the cell (Spanggaard & Krebs, 2004).

There are two major barriers limiting the promise of OPVs: low efficiencies and protection against environmental elements. The literature reports a wide range of efficiencies in OPVs in the lab and in practice – Goetzberger reporting efficiencies of 3.3% in 2002 and Zimmermann reporting efficiencies of up to 10% in 2012 – all of which are less than average crystalline silicon technologies (Goetzberger, Luther, & Willeke, Solar cells: past, present, future, 2002) (Zimmerman, Schaffer, Hugi, Fent, Corvini, & Lenz, 2012). Among the difficulties of protecting OPVs from the environment is the need to eliminate contact with oxygen. Organic solar cells typically have a half-life of only a couple hours under illumination when exposed to air (Spanggaard & Krebs, 2004).

3.2.4.3 Emerging hybrid technologies

Similar to the way sunlight interacts with unique plant organs or types of light-absorbing chlorophylls in different ways, there are also new technologies that utilize more than one strategy for utilizing solar energy in the field of photovoltaics. The hybrid strategies discussed in this section range from the solar cell scale to the integration of photovoltaic and solar thermal technologies to integration into larger building systems.

Tandem (multijunction) cells

With the emergence of a wide variety of materials being used to facilitate photovoltaic conversion of solar energy into usable electricity in the 1960s, scientists began to design multijunction solar cells that optimized efficiencies by layering materials that responded to different parts of the light spectrum (with different band gaps) (Bahrami, Mohammadnejad, & Soleimaninezhad, 2013). This strategy often uses a combination of the materials discussed in the previous section, but could use any material combination that promises to be effective at increasing efficiency.

Since the tandem strategy is rooted in the layering of any materials with photovoltaic properties, the material extraction is dependent on the materials chosen. There is the potential for these cells to have higher embodied energy since more materials are incorporated, but the ratio of energy put into material extraction and refinement to the energy harnessed may actually be lower. The tandem cell's signature combined efficiency is calculated using the efficiencies of each layer starting with the upper layer with the highest band gap, "and the lower layers will have access to the photons with lower energy that couldn't be absorbed by the upper layers" (Bahrami, Mohammadnejad, & Soleimaninezhad, 2013, p. 173). Stacking cells with different band gaps takes full advantage of the variety wavelengths found in solar radiation, consequently maximizing the efficiency of the PV module (Goetzberger, Luther, & Willeke, Solar cells: past, present, future, 2002). Bahrami reports, "the recent world record power conversion efficiencies over 40% have been achieved in II-V multijunction solar cells under light concentration using the metamorphic slightly lattice-mismatched layers" (Bahrami, Mohammadnejad, & Soleimaninezhad, 2013, p. 174).

PV/Thermal hybrid systems

Some in the field of photovoltaic research advocate for solutions that focus on utilizing solar energy that cannot be absorbed though photovoltaic processes. Photovoltaic systems can only utilize a portion of the light spectrum, but there are a number of passive systems - namely solar thermal technologies – that have successfully captured the sun's energy for human use for centuries.

Building integrated photovoltaic systems

Regardless of the technology that the photovoltaics are using, integrating them into building design can reduce the environmental impact. Establishing multifunctionality eliminates the embodied energy of the structural or aesthetic material that they are replacing. Additionally, "building integrated photovoltaics (BIPV) has several advantages: minimization of land use, offset of the cost of the PV panels if they are deliberately used as part of built structures, and better matching between power generation and power usage" (Miles, 2006, p. 1090).

3.2.5 On-site storage vs. grid-connected systems

Up to this point most of the discussion has been focused on the technology used to produce electricity. This section will focus, instead, on the fate of the electricity that is produced: whether it is used on site, stored on site, or shared with a larger network of electricity consumers. There are four broad levels of grid integration as described by International Panel on Climate Change. These include distributed off-the grid, mini-grid, distributed grid-tied systems, and centralized utility scale grid-tied systems (International Panel on Climate Change).

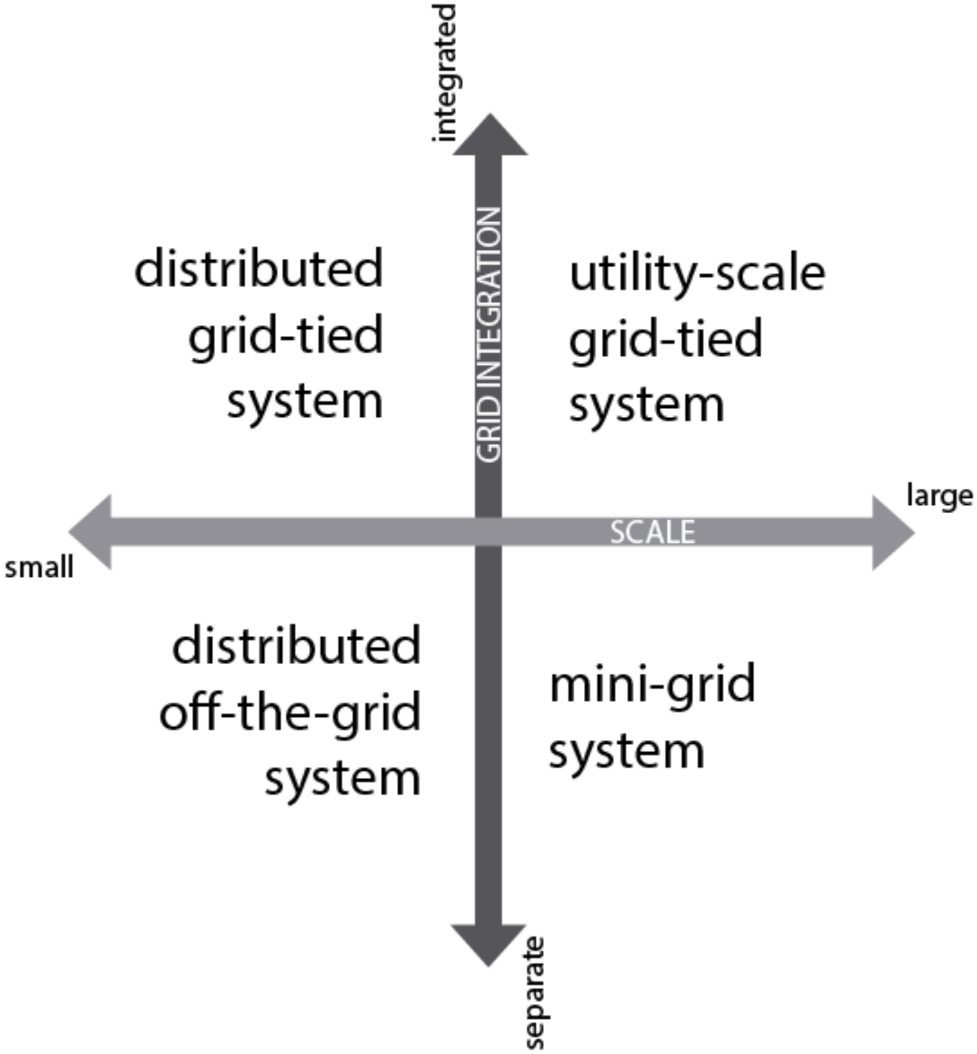


Figure 10. Types of photovoltaic systems by size and grid-integration
Developed by author

PV mini-grid systems

PV mini-grid systems are an approach between remote off-the-grid systems and full grid-connected systems. In a mini-grid, a collection of buildings in a village can be interconnected and share electricity with minimal transfer losses due to their proximity. Unlike in full grid-connected systems, this does not inherently deliver back-up energy in the event of an electricity shortage. Some communities using mini-grid systems have addressed this issue by integrating a diesel generator to the PV grid as a back-up source (International Panel on Climate Change). This photovoltaic application may be among the most cost effective for limited demand and have the greatest potential to eliminate the widespread use of diesel generators in remote areas (International Panel on Climate Change).

Distributed generation with storage

There are many advantages to distributed systems over utility-scale grid-connected systems. Since energy is generated on the site where it will be consumed, losses in transmission lines and transformers are minimized (Toledo, Filho, & Diniz, 2010). Buildings with photovoltaic arrays are able to utilize the energy produced directly by installing an inverter to convert the direct current electricity generated by the photovoltaics to alternating current, which is typically required for powering appliances and other household electronics (International Panel on Climate Change). In urban environments distributed energy generation also eliminates the need for additional land that utility-scale generation facilities require. This both reduces the associated costs and the environmental impacts of added impermeable surface. As discussed earlier, distributed generation offers the opportunity to reduce cost and environmental impact with building-integrated photovoltaics. Distributed generation also means distributed cost and distributed responsibility. Although centralized utility-scale generation can deliver cleaner energy almost as effectively, the presence of photovoltaics scattered throughout the built environment increases awareness of energy issues and may contribute to a cultural shift toward environmental responsibility, as it requires new configurations of utility organizations and governance (International Panel on Climate Change).

Off-the-grid distributed systems are typically applied in unelectrified regions of developing countries. These systems can provide great economic opportunity to these communities and promote equity by offering the community the same benefits that electrified portions of world experience, but only account for 4.2% of total photovoltaic technology installed (International Panel on Climate Change). However, the success of these systems is dependent on storage capabilities. Because of these barriers, many resources have been put toward developing effective on site storage technologies. Energy storage capacity is essential to ensuring the transition to renewable energy:

> The basis of an energy system is the capacity of this system to generate sufficient energy to attend demand at accessible prices and to provide clean, safe and reliable electricity. Therefore, electrical energy storage has always been a challenge since various electrical energy generation technologies are subject to non-linear supply based on factors such as season (hydroelectricity and wind) and intermittence (solar), without considering load changes (Toledo, Filho, & Diniz, 2010, p. 508).

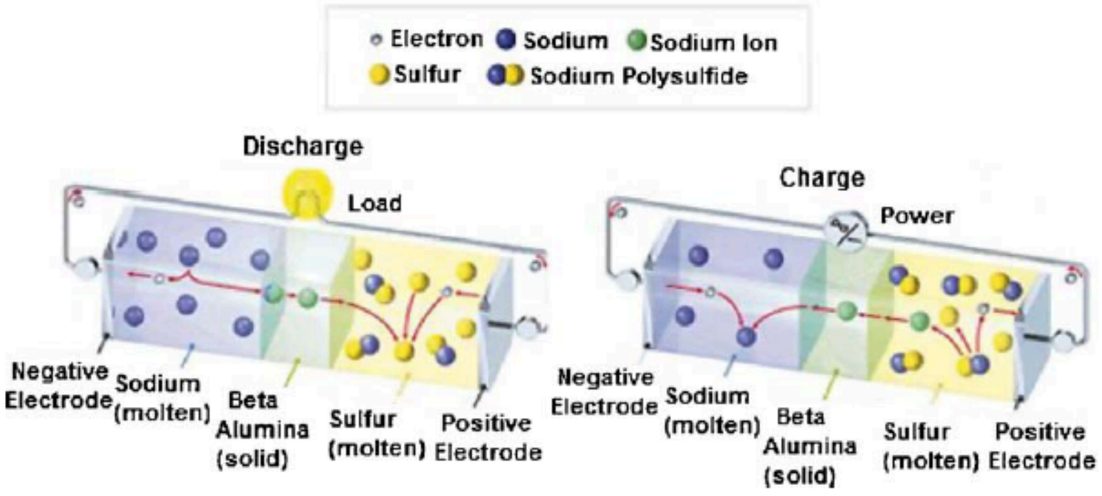


Figure 11. NaS storage technology
(Toledo, Filho, & Diniz, 2010, p. 509)

Though they have potential, current existing non-grid storage technologies leave much to be desired. Studies have pointed to *sodium-sulfur (NaS) batteries* as the optimal existing energy storage system for distributed generation systems that typically require the storage of only a few MW over a few hours (Toledo, Filho, & Diniz, 2010). NaS storage technology consists of molten sulfur positive and negative electrodes separated by a sodium beta-alumina ceramic electrolyte. The electrolyte controls the inevitable chemical reaction forming sodium polysulfide to occur in such a way that allows for the capture of electric current by forcing the electrons to move through an external circuit while the sodium ion moves through the electrolyte directly. The process is also reversible. When reversed the sodium ions that formed sodium polysulfide are liberated and return to their initial place in the sodium element (Toledo, Filho, & Diniz, 2010). One US utility company, the American Electric Power, experimented with a 1.2 MW NaS energy storage system in West Virginia and found that although the upfront costs were high, the potential annual cost saving of the system functioning at 76% efficiency was $57,000 (Toledo, Filho, & Diniz, 2010). Efficiencies around 75% are typical (Toledo, Filho, & Diniz, 2010) (Ibrahim, Ilinca, & Perron, 2008).

Though NaS batteries currently seem to be the most feasible storage systems for small-scale distributed generation, there are a variety of other emerging electricity-storing technologies that have potential. *Hydrogen fuel cells (FC-HES)* store energy using the process of water electrolysis. Excess energy during off-peak (low electricity demand) periods is used to separate hydrogen from water. The hydrogen is stored, and later during peak-hour (high electricity demand) the hydrogen is combined with oxygen from the air to create water and release energy that is harnessed as electric current (Ibrahim, Ilinca, & Perron, 2008). Efficiencies are typically low, around 35%, and life expectancy is limited (Ibrahim, Ilinca, & Perron, 2008).

Flywheels Energy Storage (FES) systems use flywheels to store kinetic, rotational energy on a short-term basis. Off-peak energy production is used to power the rotation of the device supported by magnetic bearings and operating in vacuum conditions to minimize friction (Nair & Garimella, 2010). The kinetic energy is used to generate electric current during peak-hour periods. Efficiencies for this technology drop significantly with time: 85% instantaneous efficiency, 78% after five hours, and 45% after one day (Ibrahim, Ilinca, & Perron, 2008).

Superconducting magnetic energy storage (SMES) is an emerging and high-cost energy storage strategy that yields very high efficiencies (up to 95% in the short term) and long lifespans with little loss of efficiency over time (Nair & Garimella, 2010). The operation requires the near-zero resistance superconducting cables to be hosted in very cold temperatures (-270°C), which requires power and money itself (Ibrahim, Ilinca, & Perron, 2008).

Super capacitors are an emerging and high-cost energy storage strategy that yields very high efficiencies and long lifespans with little loss of efficiency over time (Nair & Garimella, 2010). Super capacitors work similarly to electrochemical batteries except that there is no chemical reaction; instead energy is storied in an electric field between two electrodes (Ibrahim, Ilinca, & Perron, 2008).

Compressed air energy storage (CAES) is a storage strategy for large utility-scale generation facilities (Nair & Garimella, 2010). CAES involves using excess energy during low demand periods to compress air in a storage vessel (often cavernous sub subterranean volumes). When energy demand increases, the air expands releasing energy that is harnessed into usable electricity (Ibrahim, Ilinca, & Perron, 2008). The efficiency of these systems are typically around 70%, and the energy capacity is dependent on the volume – generally 12 kWh per cubic meter of storage capacity (Ibrahim, Ilinca, & Perron, 2008). Smaller systems have been used for small-scale systems, but the efficiency for those systems are typically lower, around 50% (Ibrahim, Ilinca, & Perron, 2008).

Pumped hydro storage (PHS) is generally used for large utility-scale generation facilities of 100 MWh to tens of GWh. This fairly low-tech strategy uses excess available electricity during periods of low demand to pump water from the lowest reservoir to the highest reservoir. Later, when demand exceeds supply, the water is released from the highest reservoir and flows to the lowest activating turbines that harness the kinetic energy and transform it into usable electric current. The conversion efficiency of such systems is between 65 and 80% (Ibrahim, Ilinca, & Perron, 2008).

Chemical storage systems "transform chemical energy generated by electrochemical reactions into electrical energy and vice versa, without harmful emissions or noise, and require little maintenance" (Ibrahim, Ilinca, & Perron, 2008, p. 1234). This may be the closest to photosynthesis in that energy is stored as chemical energy, however, compounds used in chemical storage for photovoltaic systems are inorganic, commonly lead-acid, nickel-cadmium, nickel-metal hydride, nickel-iron, zinc-air, iron-air, sodium-sulfur, lithium-ion, lithium-polymer, etc (Ibrahim, Ilinca, & Perron, 2008).

Distributed grid connected PV systems

Applications can be feasible in some distributed generation scenarios; however, the costs are persistently high and often make the application of storage infeasible for the aforementioned photovoltaic systems in developing countries. In many cases, distributed photovoltaic generation is tied to the grid, and uses the grid as a means of storage rather than using one of the methods discussed previously. When the electricity being generated exceeds current on-site electricity demand, the excess electricity is not wasted, but is sent to the grid to be used by another grid-tied electricity consumer. The grid acts as a battery with unlimited storage capacity regardless of seasonal and daily fluctuations in demand, but the energy that is retrieved from the grid when on-site generation does not meet demand is likely not from renewable sources (Kaundinya, Balachandra, & Ravindranath, 2009).

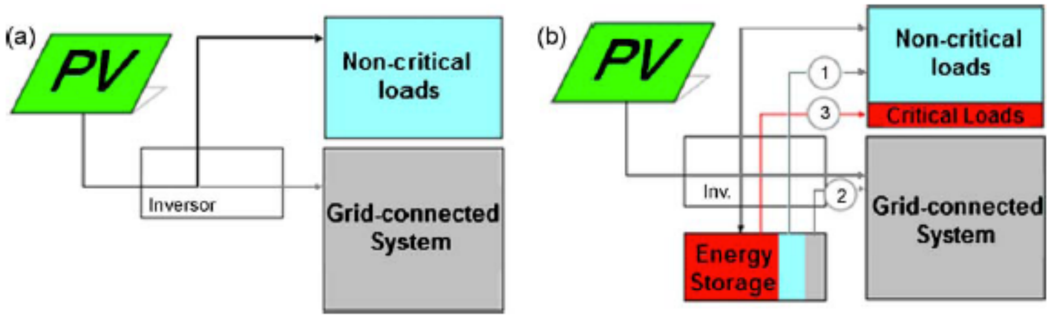


Figure 12. Grid connected systems with and without storage
Photovoltaic systems interconnected to the grid: (a) without energy storage, (b) utilizing energy storage with the following options (1) local load management, (2) load management for the utility, and (3) considering critical emergency loads (Toledo, Filho, & Diniz, 2010, p. 510).

In distributed generation grid connected systems, arrays could be installed anywhere throughout the built environment including atop residences, commercial or industrial buildings, or as a part of other elements of the built environment such as parking structures (International Panel on Climate Change). In addition to a diversity of applications for distributed PV systems, several studies have indicated that effective systems would also incorporate a diversity of energy-generating technologies. Combining PV generation with wind, solar thermal, non-renewable utility-scale generation for grid-tied systems or diesel generators for stand-alone systems increase the reliability of energy supply (Kaundinya, Balachandra, & Ravindranath, 2009).

Centralized utility-scale generation grid-connected systems

In grid-connected photovoltaic systems, there are two ways the electricity can be generated: distributed photovoltaic arrays or a centralized utility-scale photovoltaic array. Centralized utility-scale photovoltaic electricity generation allows cleaner energy with little to no required participation from the consumers because from the consumer standpoint the delivery of energy works identically to delivery from any other source. There are some economic benefits to these systems over distributed systems such as purchasing in bulk and optimizing installation costs (International Panel on Climate Change). The focus of this thesis, however, will be on distributed generation as it better aligns with the concept of biomimicry; in plant communities, energy generation and storage are both distributed throughout the community.

As a seen in the literature, there is a great deal of innovation and development happening in the broad field of photovoltaics. In the analogy analysis that will follow, I will look specifically at crystalline silicon photovoltaics as the current conventional technology. However, the developments discussed in this section will be important to the eventual envisioning of a biomimetic solar energy system.

3.3 Photosynthesis literature

This section will discuss the role of structure, process, and networks in the effectiveness of photosynthesis. Although the process of photosynthesis has existed since the first plant life began growing on earth, knowledge of the process is less than 250 years old. There are still many aspects of photosynthesis that remain unknown, including some are applicable to the design of a biomimetic solar energy system.

3.3.1 History of photosynthesis research

Photosynthesis literally means "building up or assembly by light" and refers specifically to "the process by which plants synthesize organic compounds from inorganic raw materials in the presence of sunlight" (Hall, 1999, p. 1). The initial discovery of the photosynthetic process occurred in the mid 1770s when the results of series of experiments conducted by English Chemist Joseph Priestly led to the conclusion that "green plants were able to reserve the respiratory processes of animals" (Hall, 1999, p. 22). His well-known experiments included burning a candle in three different jars: the first alone, the second containing a mouse, and the third containing a mint plant. In the first, the candle was unable to remain lit because of lack of oxygen; in the second, the mouse died for the same reason; and in the third, the candle remained lit because of the oxygen being produced by the mint plant (Hall, 1999).

After this groundbreaking discovery, research around the world commenced to more accurately define the processes involved. In 1779 a Dutch scientist reported that plants only produced oxygen in sunlight and that only the *green parts* of the plant were able to conduct this process (Hall, 1999). In 1782 in Switzerland, researchers confirmed that carbon dioxide acted as nourishment in the photosynthetic process. In the first half of the 19th century, scientists began to put together the big picture including the involvement of chlorophyll and the potential ratios of CO_2, O_2, water, and resulting organic matter:

$CO_2 + H_2O + \text{light} \rightarrow O_2 + \text{organic matter} + \text{chemical energy}$ (Hall, 1999)

Further refinement to the understanding of the photosynthetic process continued through the end of the 19th and into the early 20th century including the discovery of the 'light' and 'dark' reactions (Hall, 1999). However, it was in the 1930s that an important discovery transformed the way scientists understood the conversion of inputs into organic matter: that O_2 is evolved from H_20 not CO_2. Following these discoveries, research was focused on comparing processes in plants with varying characteristics and existing in various climatic conditions. Recent research in photosynthesis has spanned issues related to fleshing out the relationship between photosystems I and II, identifying the origins of chloroplasts, better understanding their development, and more (Hall, 1999).

3.3.2 Limiting factors of photosynthesis

There are several factors both internal to the plant and in the surrounding environment that determine the limits of the productivity of photosynthesis. Internal factors that influence photosynthetic productivity include chlorophyll content, leaf structure, accumulation of the products of photosynthesis within the chloroplast, the influence of enzymes, and the presence of mineral constituents (Hall, 1999).

Just as there are several different materials available that have different processes by which they convert light into electricity in photovoltaics, in plants there are several chemicals compounds that assist the absorption of light for the purposes of photosynthesis. Chlorophyll content determines the range of wavelengths that will be absorbed by the chloroplast. Chlorophyll is the most common light-absorbing pigment found in chloroplasts. Chlorophyll channels the captured solar energy into a “series of photochemical and enzymatic reactions” (Hall, 1999, p. 32). Chlorophyll a and b have similar structures and generally absorb the blue and red ends of the spectrum (Scott, 2008). Carotenoids are another kind of pigment that, due to their distinct structure, absorb more of the blue to green end of the spectrum and reflect yellows and reds. “The carotenoids help to broaden the range of wavelengths of light that the plant can absorb and are known as accessory pigments” (Scott, 2008, p. 21). Chlorophyll and carotenoids are bound to proteins in the thylakoid membrane and form antennae complexes to capture and redirect light energy to the photosystems to catalyze the photosynthetic process (Scott, 2008).

Similar to the construction and installation of modules within a photovoltaic array, the structure of the leaf and the arrangement of leaves belonging to a single plant also impact the productivity of photosynthesis. The structure of the leaf is determined by three functions of the leaf and how these functions are affected by the surrounding environment: the surface area affects the amount of light that can be absorbed, the thickness affects the exchange of gases necessary to photosynthesis, and the network of vascular tissue that transports materials between the leaf and the rest of the plant (Scott, 2008).

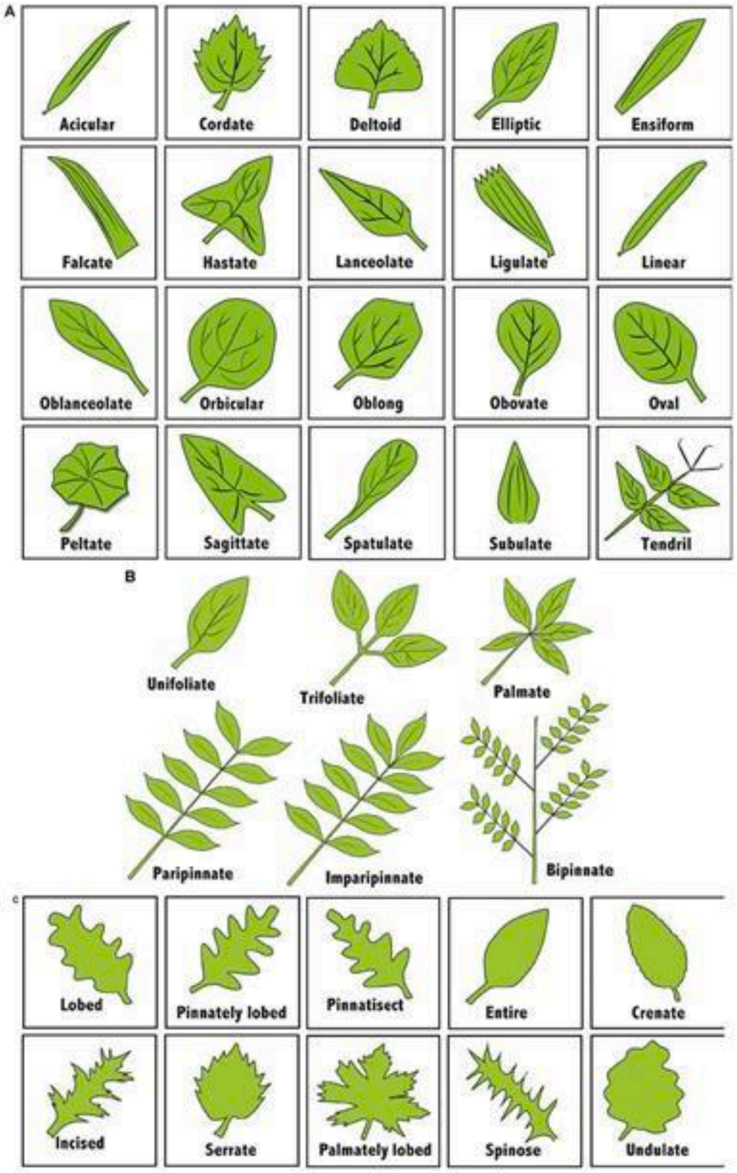


Figure 13. Leaf structures
(Scott, 2008, p. 18)

Based on the variety of leaf shapes and sizes, it has been suggested that there is no universal leaf structure that is optimal for photosynthesis. Figure 13 illustrates some of the shapes and sizes found to be effective. Additionally, the arrangement of leaves on a single plant is partially determined by photosynthetic needs (Scott, 2008). The variety of leaf arrangements are illustrated in Figure 14.

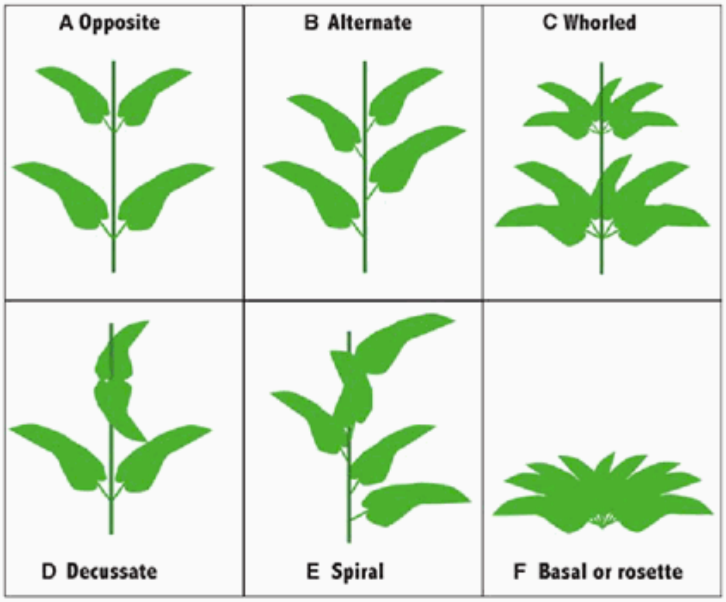


Figure 14. Leaf arrangements
Lead initiation by the meristem. Periodically, the tunica cells divide more rapidly in synchronous manner, some to form leaf primordia. Leaves are formed in a very ordered way by the meristem and some of the described forms of leaf arrangements are shown. (Scott, 2008, p. 155).

Unlike excess energy in photovoltaic systems, the accumulation of the products of photosynthesis that build up in the chloroplast affect the process of photosynthesis. There is a ceiling on the storage capacity of each kind of carbohydrate that is produced. Sucrose is produced first, filling the cytosol and then filling the vacuole. When the vacuole is at capacity, sucrose is exported to other areas of the plant. When sucrose capacity is met, the production of carbohydrates transitions to producing starch, which can be used within the leaf to support metabolic activity (Scott, 2008).

The surrounding environmental conditions also impact the rate of photosynthesis. The external factors that influence photosynthetic productivity include light intensity, ambient temperature, concentrations of CO_2 and O_2 in the surrounding air, and the availability of water and nutrients (Hall, 1999). Early studies conducted on algae species showed that in typical atmospheric conditions, there is a linear relationship between light intensity and the rate of photosynthesis at low light intensities. However, at mid-to-high light intensities the rate of photosynthesis first increases at a slower rate and eventually plateaus (Hall, 1999). Only a fraction of the light that reaches earth's surface can be utilized in photosynthesis. This fraction is called photosynthetically active radiation (PAR) and consists of light energy between 400 and 740mm (Smith & Smith, 2008). Further research has concluded that most plant species, with the exception of ground cover in dense forests, receive sufficient sunlight to saturate their photosynthetic capacity given other limiting factors are not at play (Hall, 1999). However, in some plants incident light exceeding the light saturation point can actually reduce photosynthetic productivity, which is referred to as photoinhibition (Smith & Smith, 2008).

In contrast, at low light intensities, the effect of temperature is nearly undetectable. However, at medium to high light intensities slight differences in ambient temperatures yield great differences in photosynthetic rates (Hall, 1999). The same pattern is true of CO_2 concentrations, however, the ability to uptake CO_2 is also highly dependent on the rate of transpiration, which is dependent on the diffusion gradient of concentrations of water inside the plant and in the surrounding air. When there is a significant deficit of water available to the plant to uptake through the roots, the stomata close to minimize water loss, which inhibits the uptake of CO_2 through the stomata greatly limiting photosynthetic activity (Smith & Smith, 2008).

The availability of nutrients such as phosphorous and nitrogen externally affect the concentrations of such nutrients in the photosynthetic cells consequently determining the rate of photosynthesis. When the availability of phosphorous in the soil is low, plants often respond by prioritizing root growth over shoot growth (Scott, 2008). Additionally, when the availability of inorganic phosphorous in the leaves is low due to low availability in the soil, photosynthesis cannot commence.

3.3.3 Plant processes enhancing photosynthetic productivity

There are many interconnected, environmentally stimulated processes that adjust the rate of photosynthesis appropriately to support the well being of the plant as a whole. Some of these processes are well documented and understood, while "it should be admitted that even now we do not understand fully certain aspects of photosynthesis" (Hall, 1999, p. 24).

The photosynthetic process feeds on available solar radiation. For most plants, the times of day and times of year during which ample solar radiation is available for photosynthesis is predictable and accompanies changes in external environmental conditions such as light and temperature (Scott, 2008). The circadian clock mechanism regulates the expression of certain genes throughout a daylong period in response to variations in temperature and light availability to support plant fitness (Scott, 2008). Photoperiodism helps the plant orient itself in the time of year by sensing the changes in day length. This helps the plant optimize energy put toward seed production and flowering to ensure the greatest chance of successful distribution of seeds and their survival (Scott, 2008). There are several other physical responses to changes in day length aside from reproduction, but available research in the literature is limited (Scott, 2008).

There are many examples of plants *moving* in response to an environmental stimulus, whether moving to take advantage of the environmental condition or moving to avoid it. There are two categories of plant movement: tropic and nastic movement. Tropic movements involve "the directional movement of a plant, or part of a plant, in response to a stimulus; examples include a plant's response to light or gravity" (Scott, 2008, p. 161). There are many different tropisms in plants responding to a variety of stimuli. Phototropism is the phenomenon in which the auxin, a plant hormone located at the tip of the stem, sends signals to the rest of the plant and triggers growth in the direction of the light source (Scott, 2008). Light triggers the auxin to induce growth on the dark side causing the stem to grow in the direction of the light source over time. In heliotropism, plants move following the movement of the sun. Though this process is not as well understood as phototropism, it is known that the response occurs not in the flowers, but instead in the stem immediately below. Leaves can also move to track the sun either positioning their leaves to be perpendicular to the sun to maximize solar gain (diaheliotropism) or angle the leaves to reduce the incident light in response to drought (paraheliotropism) (Scott, 2008). There are also trophic movements in response to gravity (toward in the roots, away in the shoots), water, touch, and certain chemicals.

The other category of plant movement includes nastic movement, which "occurs when a plant responds to an external stimulus but the movement is independent of the direction of the stimulus" (Scott, 2008, p. 161). The stimuli include, but are not limited to, time of day (circadian rhythm), mechanical stimulation (shaking, wounding or burning), and temperature (Scott, 2008).

3.3.4 Stress and defense responses

After millions of years of evolution many plants have developed strategies to protect themselves from exceptionally harsh environmental conditions and impacts of development.

Due to the constant fluctuation of available photosynthetically active radiation (PAR), plants generally do not experience permanent damage with rapid changes in PAR. However, when long-term disruptions in PAR occur plants must adjust beyond altering the rate of photosynthesis. These larger adjustments could involve shifts in biochemistry, physiology, or morphology (Smith & Smith, 2008). Morphologically, plants that constantly compete for sunlight may develop larger, thinner leaves to maximize uptake of PAR. Biochemically, they also tend to allocate more carbon to the leaves than to the roots (Smith & Smith, 2008). Similarly, intense prolonged increases in PAR can also result in decreased rates of photosynthesis.

Both too much and too little water available to a plant can effect photosynthetic productivity. During drought conditions, when water availability is extremely low, among the first responses plants typically have is to direct energy toward the growth of roots rather than shoots and leaves. This both allows the plant to better its ability to uptake water from the soil and limit the amount of water lost due to transpiration through the leaves. However, the root system cannot grow beyond the leaves capacity to conduct photosynthesis to support them (Scott, 2008). Leaves may also respond by closing the stomata – the pores that allow gases to enter and exit the leaf – which limits the loss of water, but also limits the exchange of carbon dioxide and oxygen, which in turn reduces the ability to photosynthesize (Scott, 2008). C4 and CAM plants, found in dry regions, have alternative photosynthetic processes to deal with drought conditions rather than evolved responses to the stress of limited water. These plants are often found in climates in which drought conditions are common and have evolved to be better equipped to survive extreme or prolonged droughts. In the moderate climates plants can be exposed to both extreme excess of water and drought, and too much water can be just as detrimental to photosynthetic productivity as too little. Flooding limits the availability of oxygen to support aerobic respiration, therefore slowing or halting the production of ATP and NADH critical to the photosynthetic process (Scott, 2008).

In moderate climates, plants are subjected to both prolonged cold and heat throughout the year. Extreme temperatures are really drivers for conditions that put stress on photosynthetic productivity, rather than affecting it directly. During cold periods, plants have to deal with low temperatures, reduced PAR availability and inaccessibility of water due to freezing. Deciduous trees have evolved to withstand these stressors by absorbing the contents of their leaves to be stored and shedding them and their vulnerability for the season (Scott, 2008). During warm periods, water available for the purposes of photosynthesis may be limited because it is being evaporated directly from the surface or soil and is therefore unavailable to be taken up by the roots or because rates of transpiration are increased to keep the leaves cool in times when solar radiation is particularly intense. To combat the stress of these high-temperature-related conditions, leaves may move to reduce the light intensity (Scott, 2008).

The processes and characteristics listed in this chapter, although not exhaustive, provide insight into the complexity of photosynthesis-supporting characteristics of plants. There will be a more in depth explanation of the mechanics of photosynthesis at varying scales within an ecosystem in Chapter 6. The combination of the mechanics of photosynthesis and the photosynthesis-supporting processes discussed here will inform the eventual envisioning of a biomimetic solar energy system.

4 Constructing a biomimetic lens

The purpose of this section is to clearly define the way in which biomimetic thinking will be applied to the conception of a new solar energy system. Amidst the many definitions, applications, and theories stemming from different cultures and disciplines, I have custom constructed an accessible biomimetic lens to best fit the needs of this study. It should be noted that although Biomimicry 3.8, a leading organization in biomimicry education, also uses a "Biomimicry DesignLens," the content of the lens constructed in this study is original and was derived from my own interpretation of the literature following a rigorous review (Biomimicry 3.8). The inspiration for the "lens" terminology comes not from Biomimicry 3.8, but instead from system scientist Bela Banathy who equates a lens to a world-view that becomes the means through which we construct our internal reality from the physical world we perceive (Banathy).

As found in the review of biomimetic literature, there are many divisions between biomimetic design approaches based on:

- The purpose of biomimetic thinking
- The method of transfer of information from one field to another
- The scale(s) of systems being mimicked and scale of systems being designed
- The point(s) within the design process that include biomimetic thinking

For the purposes of this thesis, I will discuss levels of biomimicry as they relate to the ability to design sustainable systems.

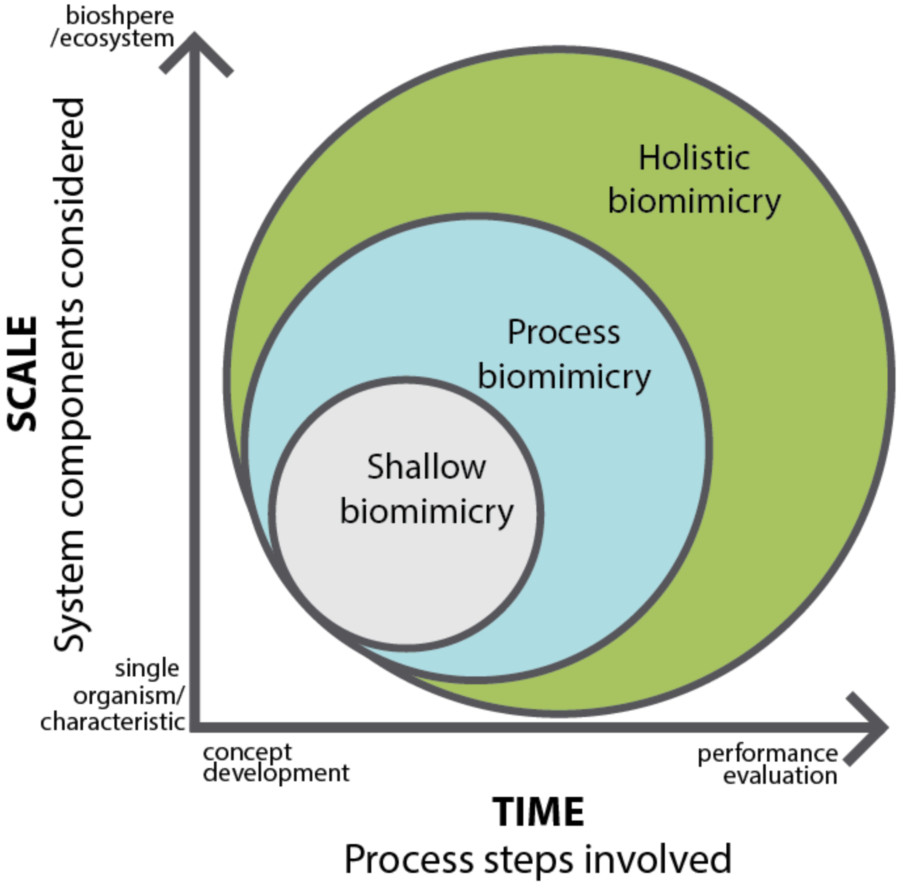


Figure 15. Shallow, process, and holistic biomimicry as it relates to system scale and design process
Developed by author

4.1 Levels of biomimicry

When the term ‘biomimicry’ is dissected into its fundamental pieces the result is: ‘bios’ meaning life and ‘mimikos’ meaning to mimic. Though this definition may seem definite and objective, throughout time and across disciplines biomimetic researchers and practitioners have strayed from this fundamental definition in a wide variety of directions.

Shallow biomimicry

Nearly every author included in the literature review agreed that biomimicry, at its core, is a design mindset, an attitude toward design that serves as a source of inspiration for innovative design. Whether it’s using nature as a “source of innovation” based on casual observations and experiences or a more rigorous “study” of specific biological or ecological principles, it appears that inspiration is a critical part of successful biomimicry (Zari, 2010) (Volstad & Boks, 2012). Many times, the result of inspirational biomimicry is the mimicry of form without connection to the function of the mimicked organism. One example, provided by Petra Gruber, is Luigi Colani's exhibition inspired by Ernst Haeckel. He drew inspiration from the aesthetics of the biological organisms represented in Haeckel's drawings, but the function of the organisms did not translate into the design (Gruber, 2011).

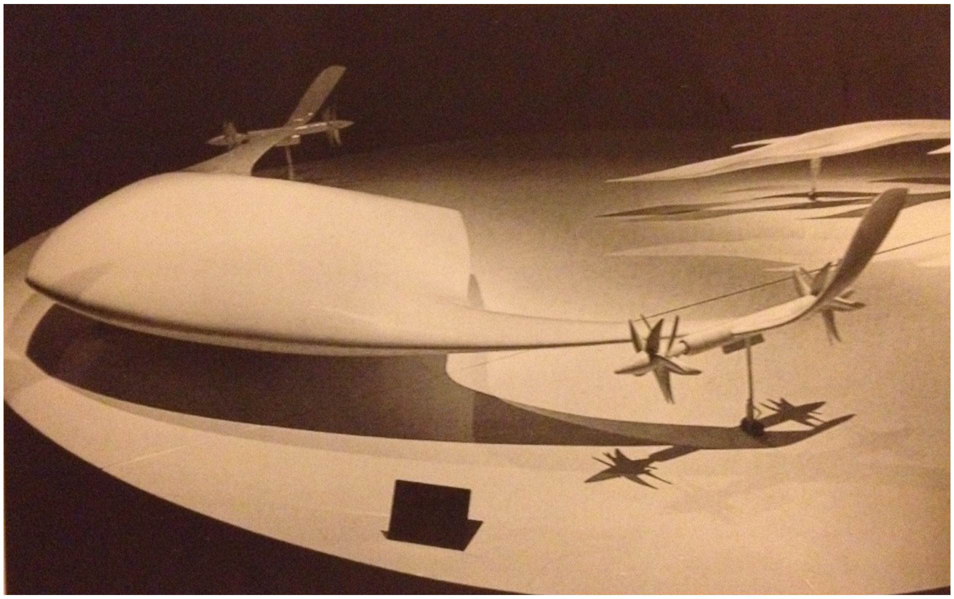


Figure 16. Luigi Colani Model, Design museum exhibition 2007
(Gruber, 2011, p. 41)

However, many biomimetics also assert that when designers are consciously inspired by some biological or ecological principle, structure, or pattern, but do not extend that initial source of inspiration into their design methodology they are practicing 'shallow biomimicry.' According to one of those biomimetics, Petra Gruber, "going beyond the mere translation of form is the challenge that biomimetics in architecture is about" (Gruber, 2011, p. 42).

Process biomimicry

A deeper biomimicry is found in mimicking biological processes rather than the aesthetic or structural aspects of biological entities. Process biomimicry can include climate strategies (passive ventilation, cooling and heating), sensory strategies (detection and processing of physical or chemical stimulation), locomotion strategies (walking, swimming, flying), or other biological processes such as photosynthesis and material recycling (Gruber, 2011). In order to achieve process biomimicry, the transfer of biological concept to design requires more than just inspiration. Abstraction and analogy, instead, serve as methods for transferring complex biological processes into a form that is accessible to the designer and appropriate for the specific application.

Analogy can be a powerful tool for translating concepts from one field to another because of its role as a process for explaining or clarifying complex concepts. Werner Nachtigall, biomimetic researcher and cofounder of the Society for Technical Biology and Biomimetics, praises analogy for its accessibility, which makes it a good non-scientific starting point for exploring concepts in a field other than your own. It is an "impartial, open-minded comparison, [and] if examination shows that the comparison makes sense, further questions can be raised and more detailed investigations e.g. on formal and functional features carried out" (Gruber, 2011, p. 43). Four examples of analogy between non-human 'nature' and human technology presented by Nachtigall are found in Figure 17. However, analogy is still an early step in biomimetic design. Both Nachtigall and fellow biomimetic thinker Frei Otto see analogy as a starting point. Otto asserting, "objects can be similar or equal in form, gestalt, construction, structure and material [but] they may have acquired this analogy through identical, similar or completely different development processes" (Gruber, 2011, p. 43). Steven Vogel brings up the concern of scale in analogy. There can be valid applications for analogy between natural and technological structures or processes that are of different scales, but "the relationship between length, surface, and volume is not linear, and all physical processes are affected by this phenomena" (Gruber, 2011, p. 44). Therefore, when translating concepts between fields to applications of vastly different scales, these differences need to be accounted for.

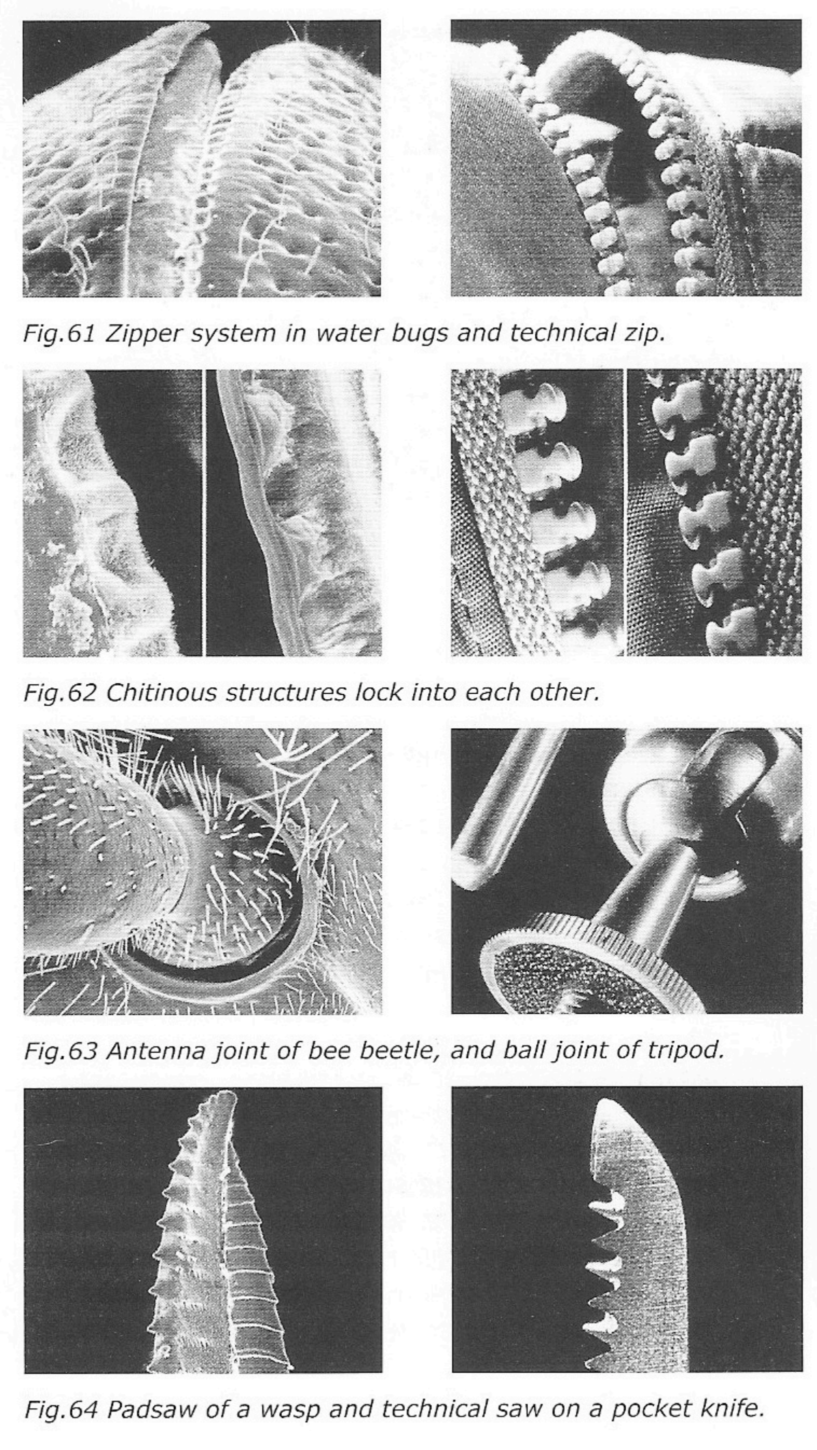


Fig.61 Zipper system in water bugs and technical zip.

Fig.62 Chitinous structures lock into each other.

Fig.63 Antenna joint of bee beetle, and ball joint of tripod.

Fig.64 Padsaw of a wasp and technical saw on a pocket knife.

Figure 17. Analogy between nature and technology as presented by Werner Nachtigall
(Gruber, 2011, p. 43)

Holistic (ecosystem) biomimicry

Holistic biomimicry includes not only inspiration and applied analogy, but also the study of relationships between the designed and its context. Holistic biomimicry, or *ecosystem biomimicry*, involves mimicking not only the form and/or function of the natural world, but also the system of information, material, and energy exchange with the surrounding environment, just as in ecosystem science.

Abstraction is often necessary to delve deeper into the analogous relationships between processes in the world society perceives as 'nature' and the socio-technological world we take ownership of. Abstraction through modeling is used by both biologists investigating processes and phenomena in non-human systems and engineers and architects designing the built environment (Gruber, 2011). Modeling complex processes allows better translation of more than form and process, but the reasons behind the development of those forms and processes as well as their relationships to the larger ecosystem. BioTRIZ is one very systematic approach outlined in *Biomimicry: It's Practice and Theory* by Julian Vincent, which calls for abstracting and transferring concepts for biomimetic design. This process was detailed in the Literature Review chapter. However, it is not used here because it implies a clear problem-solution approach. The biomimetic lens constructed and applied in this thesis aims to mimic nature's solutions to specific problems and the interconnections between nature's solutions to problems existing in nested systems.

4.2 Biomimicry in the design process

Shallow biomimicry is often only involved in the early stages of the design process, whereas process and holistic biomimicry can be integrated throughout the design process including but not limited to concept development, design, implementation, and assessment.

Biomimicry as a methodology suggests that biomimetic thinking not only provides the initial inspiration, but also transforms the way in which the design and construction are carried out through emulating, imitating, or mimicking biological or ecological principles. Although the scope, originating discipline, and intention of each piece of literature led each author to a distinct set of key biological and/or ecological principles to mimic, patterns were found across the literature as a whole, and a framework of common principles began to emerge. Nearly every biomimetic reviewed in the literature had his or her own set of design principles that are ideal to mimic. Through my own review of that literature, ten common design principles for mimicking non-human organisms and systems emerged in four larger categories: (1) system-based organization, (2) dependence on local conditions, (3) diversity that supports resiliency, and (4) repurpose of waste. These principles not only serve as a foundation for the design process, but also for determining whether the resulting design is successfully biomimetic.

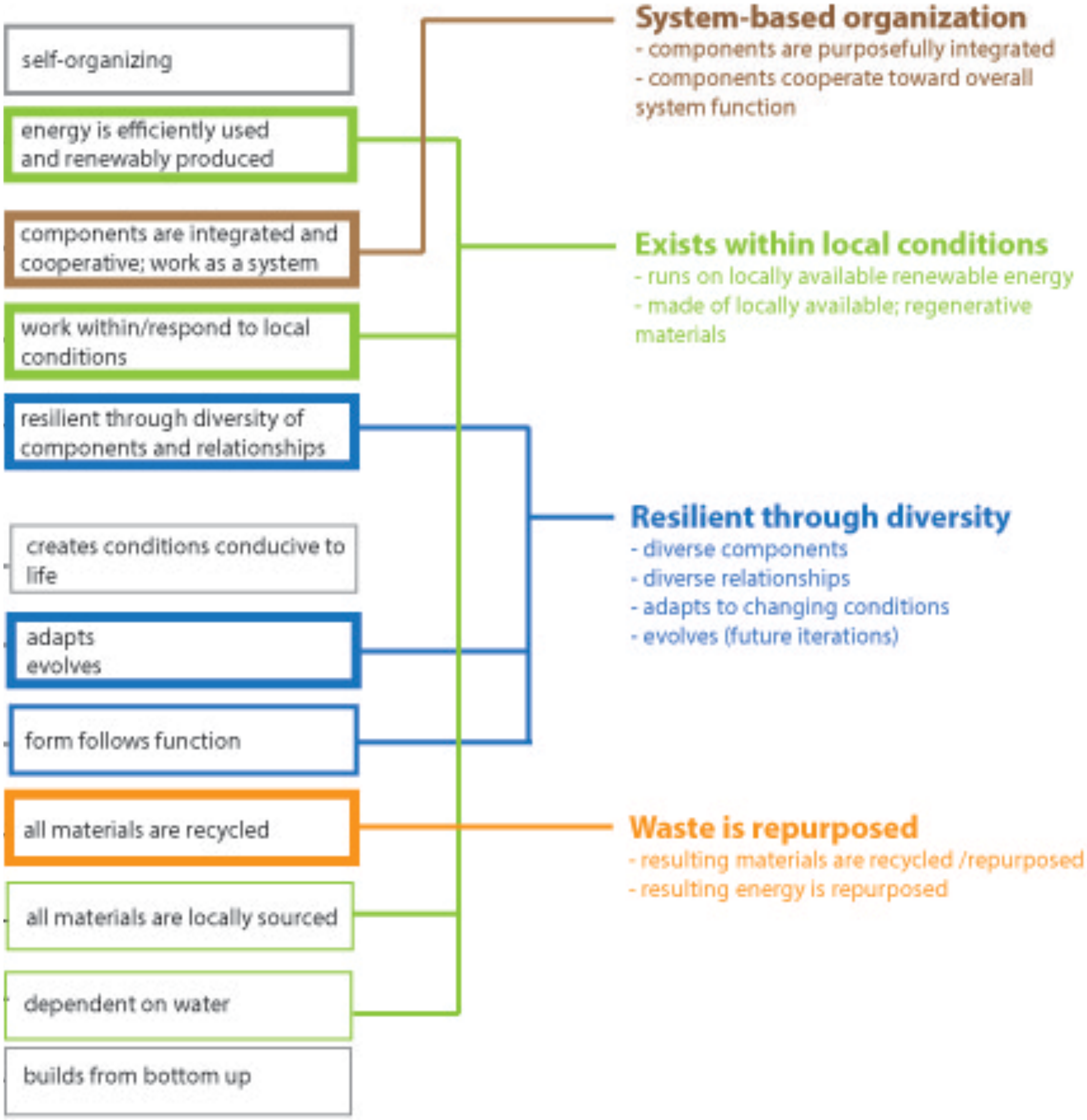


Figure 18. Synthesis of common biomimetic principles found in the literature
Developed by author

Biomimicry as a tool for *achieving sustainability* in the design and construction of the built environment must include using biomimicry as a measure of success. Janine Benyus calls for a biomimicry that uses nature as a measure against which to gauge the 'rightness' of our innovations (Benyus, 1997). The built environment has a large negative effect on ecosystem health and ecosystem services. According to Zari,

> one way to reduce this is by creating built environments that mimic or provide these ecosystem services and therefore reduce pressure on ecosystems…This is different from design methods such as industrial, construction, or building ecology, or in fact process-level ecosystem biomimicry, because it moves beyond mimicking ecosystem as a metaphor (Zari, 2010, p. 178).

Current methods for assessing sustainability in the built environment, such as the US Green Building Council's Leadership in Energy and Environment Design (LEED) rating system, do not hold up against the rigor of a biomimetic system of assessment. Bill Browning of the consulting firm Terrapin Bright Green explains, "…LEED is just a design-phase measurement tool; it provides neither a set of performance goals nor a source of inspiration to achieve these goals" (Terrapin, 2011, p. 1). Holistic biomimicry that uses ecological principles as both guides for determining success and inspirational material goes beyond sustainable design strategies like LEED. There are a variety of emerging methods for measuring the extent to which applying ecological principles to the design of an object or system resulted in the successful mimicking of nature's processes including the Living Building Challenge rating system discussed in the literature review and Zari's framework, both of which calls for testing the function of the new biomimetic design against the ecosystem services provided by non-human nature (International Living Future Institute, 2012) (Zari, 2010).

4.3 The constructed lens

The biomimetic lens that I have constructed incorporates dimensions of time and scale in the application of the core principles of what we perceive as 'nature' to the design of the built environment. The result of applying the biomimetic lens will be a suggested process for conceiving, designing, and assessing a biomimetic solar energy system from the solar cell to the panel to the array to the community. The biomimetic lens, found in Figure 19, will be applied to both the mechanics of photosynthesis and the mechanics of photovoltaics outlined in the following sections to incorporate ideas that emerge from both a top-down and bottom-up approach to applied biomimicry.

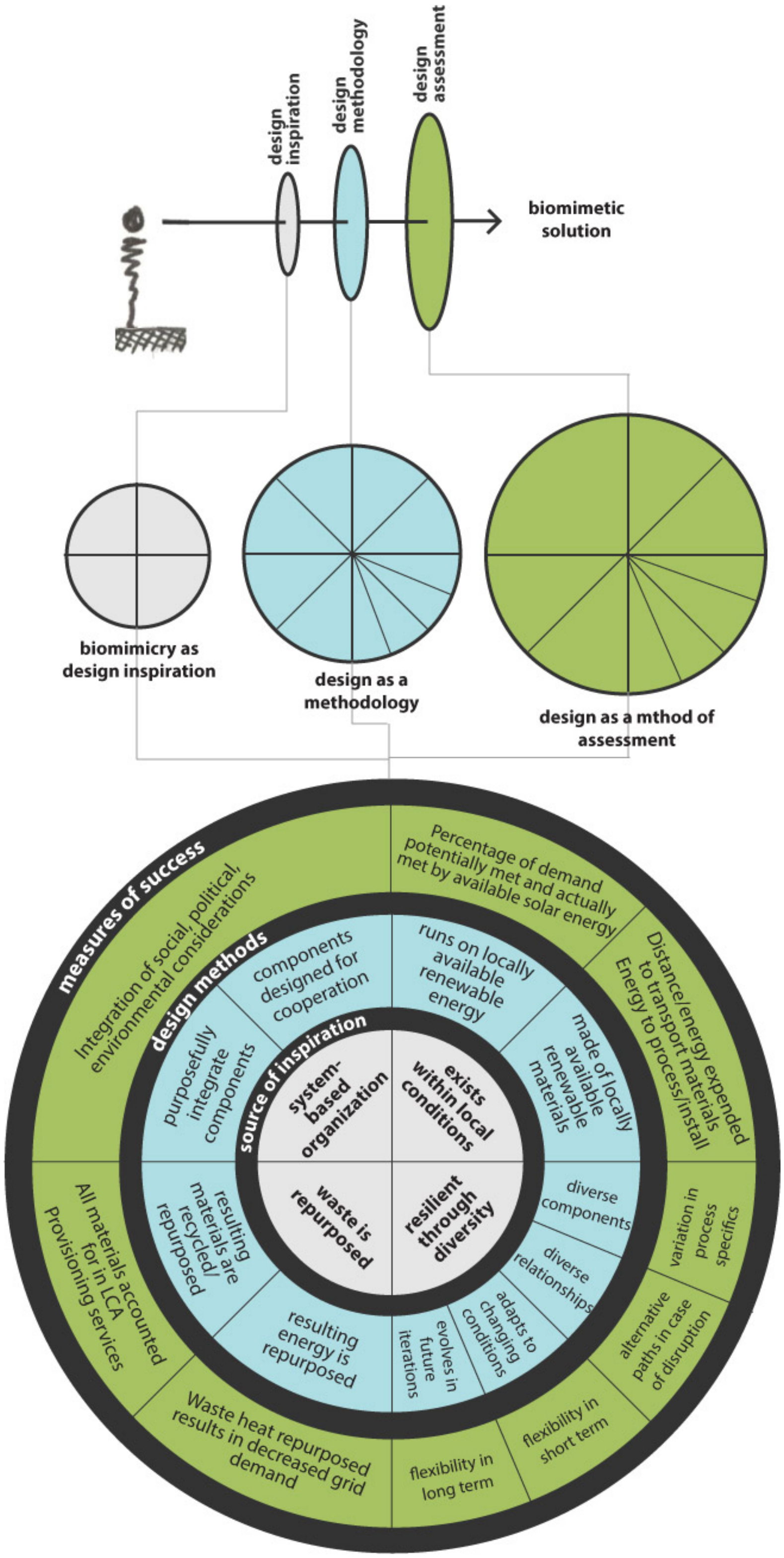


Figure 19. The biomimetic lens
Developed by author

As a result of the multifaceted definition of biomimicry, the biomimetic lens must address both the variation in scale and in the point in the design process at which biomimetic thinking is being applied. First, there are four areas of inspiration that should get biomimetic designers started in conceptual development. Further, there are several specific design methods that should guide them through the design process within each of the four areas of inspiration. These can and will be applied to the various scales related to the overall solar energy system. Finally, holistic biomimicry demands measuring success against natural systems. Determining the appropriate metrics and goals will be dependent on local conditions. The purpose of the biomimetic lens is to provide general guidance for turning the definition of biomimicry into a process for achieving it. The next two chapters will outline the biological system involved in the photosynthetic process and the sociotechnical system of photovoltaic energy. Finally, in the following chapter, this biomimetic lens will be applied to suggest biomimetic solutions to the design of a sustainable solar energy system.

5 Mechanics of photosynthesis

This chapter includes a detailed description of the systems involved in photosynthetic activity including all elements (and their potential attributes), their interconnections to one another, and their contribution to the overall function of the system. To make this system investigation more manageable I will break the system into four subsystems based on scale: the photosynthetic cell, the leaf, the plant, and the ecosystem. I will build from energy production to energy use within the plant to energy distribution and cooperation of the biological system supporting photosynthesis. Each scale will be studied as its own system with clearly defined boundaries and of those that lie outside the boundary only those elements, attributes and interconnections that directly interact with the defined system and either drive or hinder the function of the system will be explored as *environmental elements*. *Elements* include tangible and intangible 'nouns' that interact with one another and contribute to the function of the system. Their *attributes* are the 'adjectives' that describe the condition of the elements. The *interconnections* include any relationships between two elements be it a transport of physical material, energy or the exchange of information. All of these elements and interactions drive the subsystem, and ultimately the larger photosynthetic system, toward a particular *function*.

The systems driving photosynthetic activity can be studied both *across scales* and *across time*. Plant-related systems are cyclical across time. See Figure 20 for a system map of a plant lifecycle and the necessary inputs and consequent outputs at each life stage. Seed germination and plant growth are dependent on the nutrients provided by the decay of other neighboring plants from a previous time. Growth is followed by a period of reproduction and sustaining life, which contributes to the first stage of the next plant's germination. Finally, at the end of the plant's life, it decays and contributes to the ecosystem.

Although I acknowledge that there are changes to the system across time, and incorporate temporal changes to the system, the majority of this study is focused on the differing scales during the reproduction/sustaining life periods since these constitute the majority of a plant's life.

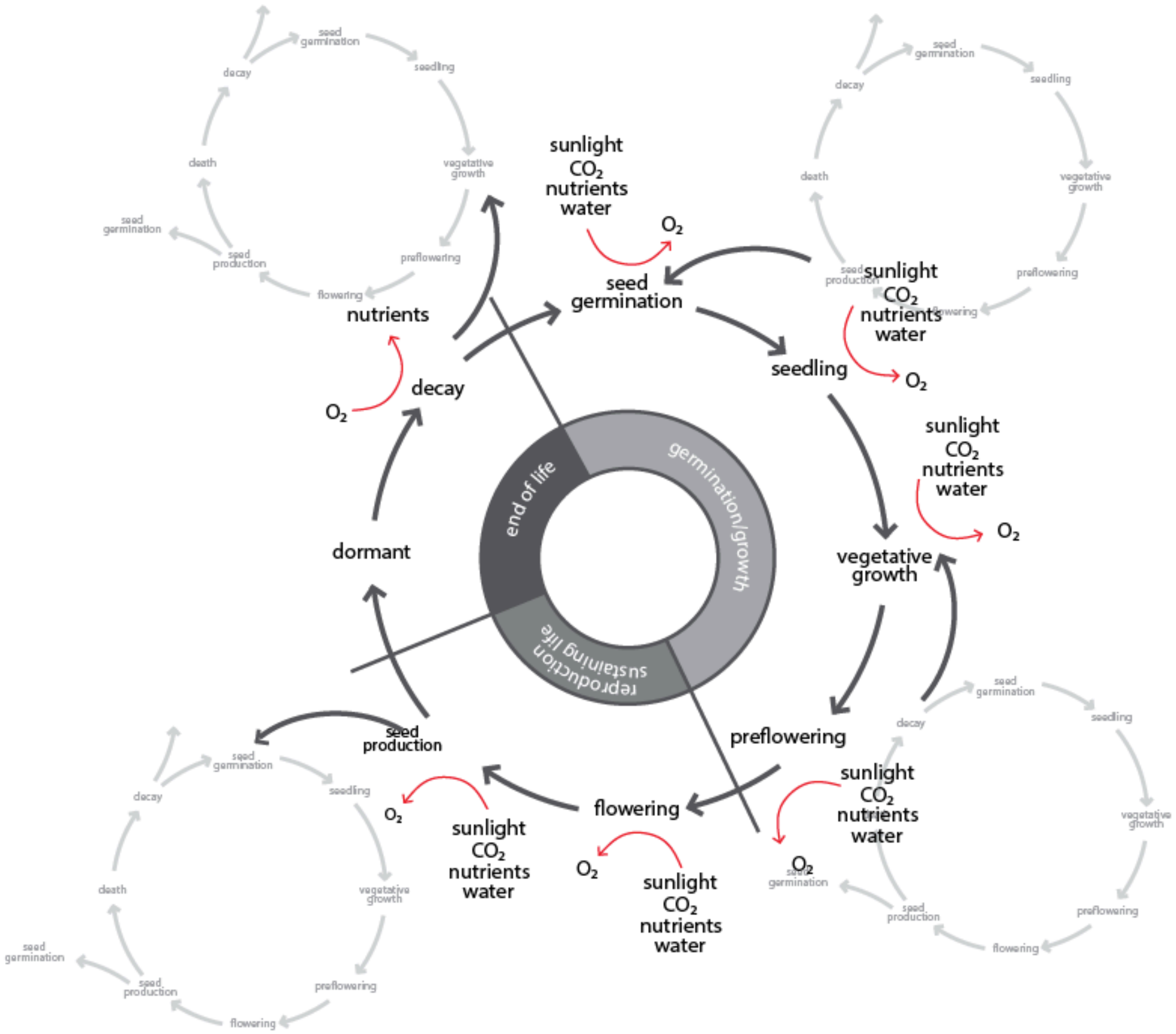


Figure 20. Plant lifecycle with inputs, outputs, and interconnections with other plant systems
Developed by author

5.1 The photosynthetic cell

The boundaries of the photosynthetic cell system can be defined as the outer membrane of the individual cell and any environmental elements that might physically interact with the membrane. This includes the photon that penetrates the membrane and the surrounding plant cells within the leaf. The function of the photosynthetic cell is to carry out photosynthesis to both produce chemical energy and carry out the process of respiration – the release of oxygen (O_2).

Environmental elements	Photons				
	Photosynthetic cells				
	Protective cells				
	Vascular cells				
Internal elements	Cell wall	Plasmodesmata			
	Vacuole				
	Nucleus				
	Mitochondria				
	Peroxisome				
	Golgi				
	Endoplasmic reticulum				
	Chloroplast	Chloroplast envelope	Outer membrane	Chlorophyll/Carotenoids	
			Inner membrane		
		Stroma		Protons	
				ADP / ATP	
				NADP+ / NADPH	
				Water	
				Carbon dioxide	
				Inorganic phosphate	
				3PGA	
				Carbohydrates	Sucrose
					Starch
				RUBISCO	
		Grana	Thylakoid membrane	Photosystem II	
				Plastoquinones	
				Cytochrome	
				Plastocyanin	
				Photosystem I	
				ATP synthase	
				Electrons	
			Thylakoid lumen	Water	
				Protons	

Table 06. Environmental and internal elements involved in photosynthesis
Developed by author

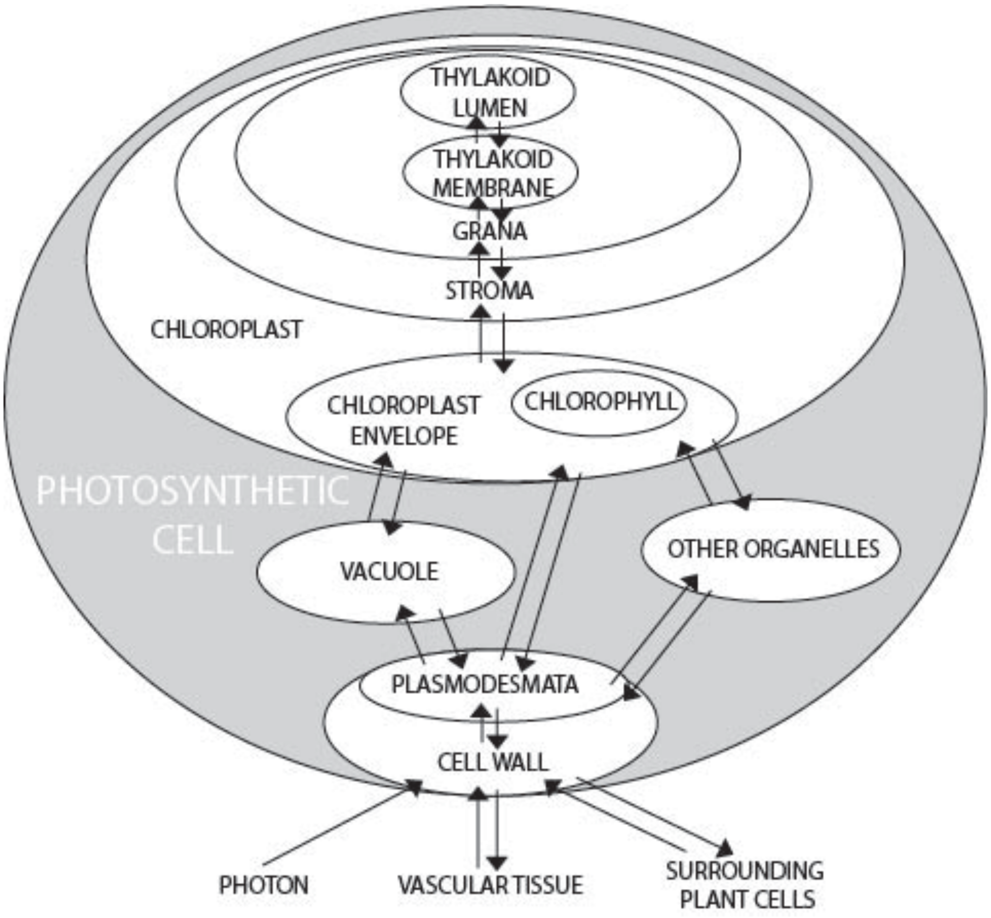


Figure 21. Photosynthetic cell system (simplified)
Developed by author

Environmental elements

The driving element of the photosynthetic cell system is the *photon*. Albert Einstein, building off the work of Max Planck, proposed that light energy was transmitted as pockets of energy, which he called *photons* (Hall, 1999). The amount of energy that is contained in any given photon is dependent on the frequency (an inverse of the wavelength) of the light. The photon hits the pigment in the leaf and its energy is used to excite an electron and catalyze the photosynthetic reaction. However, the amount of energy in the photon must match the specific energy needed to excite that electron: the critical energy (Hall, 1999).

The photosynthetic cell is but one of several types of cells found in the leaf. Each photosynthetic cell is surrounded by other *neighboring photosynthetic cells* that also carry out the photosynthetic process; *vascular tissue* transporting nutrients and other materials; and *protective cells* including the palisade, epidermis, cuticle, and lower epidermis. Most of the interaction between a single photosynthetic cell and the surrounding plant cells is powered by the existence of a chemical gradient.

Internal elements

The outside most layer of the photosynthetic cell is the *cell wall*. The cell wall serves as both a structural component of the plant and a protective filter for individual cells. Most plants also contain pathways through cell walls connecting two plant cells to one another. These pathways are called *plasmodesmata*, and they allow solutes to move between cells (Scott, 2008). The *vacuole* acts as a reserve for storing compounds including sucrose produced during photosynthesis (Scott, 2008). It can exist as one large volume (common in mature cells) or a series of small pockets (common in immature cells), and it can expand to support cell growth without the synthesis of new cell material (Scott, 2008).

There are many critical *organelles* within the plant cell that support the conditions necessary to carrying out photosynthesis aside from the chloroplast where photosynthesis actually takes place. However, their functions are more loosely related to the actual energy-producing piece of the photosynthetic process so they are not outlined in as much detail in this study. These supporting organelles include: the nucleus, mitochondria, peroxisome, golgi, and endoplasmic reticulum (Scott, 2008). *Chloroplasts* are cellular plastids in which photosynthesis takes place, and will be the focus of this section. In the average plant, chloroplasts occupy approximately 8% of total cell volume in leaves (Hall, 1999). The structure of the chloroplast can be seen in Figure 22.

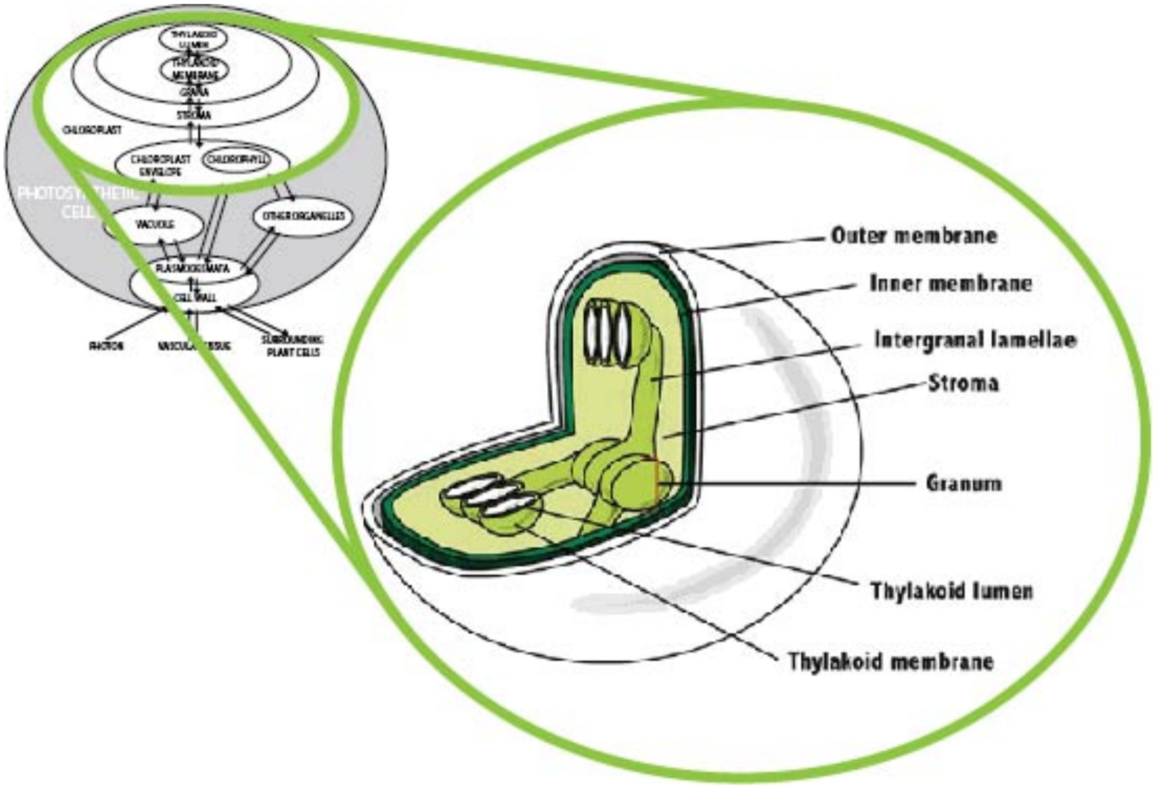


Figure 22. Structure of the chloroplast
Left: Developed by author
Right: (Scott, 2008, p. 13)

Within the chloroplast, there are light-absorbing pigments called *chlorophyll* and *carotenoids*. Chlorophyll is the most common light-absorbing pigment found in chloroplasts. Chlorophyll channels the captured solar energy into a "series of photochemical and enzymatic reactions" (Hall, 1999, p. 32). As outlined in the literature review, chlorophyll a and b have similar structures and generally absorb the blue and red ends of the spectrum whereas carotenoids absorb the blue to green end of the spectrum and help the cells absorb light more effectively (Scott, 2008). They are both bound to proteins in the *thylakoid membrane* (Scott, 2008).

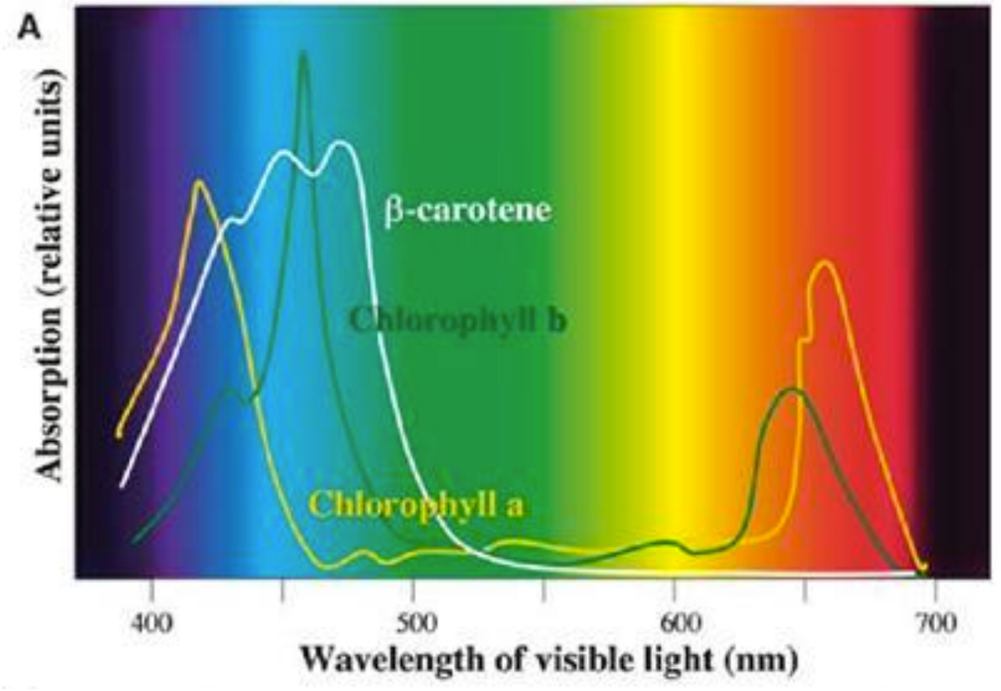


Figure 23. Light absorbed by chlorophyll and carotenoids
(Scott, 2008, p. 22)

The *chloroplast envelope* is a double-layer membrane consisting of an outer and inner layer. Similar to the cell wall, this protective layer is semipermeable and allows solvents to move in and out of the photosynthetic cell. It also holds the stroma. The *stroma* is a colorless matrix in which the several processes take place including the production of sucrose (the main chemical product of photosynthesis) during the 'dark reaction' of photosynthesis, which will be outlined below. The stroma is also the material in which the *grana* are suspended (Scott, 2008). Each granum possesses the necessary components to carry out the light reaction of the photosynthetic process (Scott, 2008). The *thylakoid membrane* is the protective layer of the grana. This lipid bilayer contains the two photosystems necessary to carry out the light reaction of photosynthesis as well as several enzymes necessary to the proces. It also is the barrier that allows protons to build up in the thylakoid lumen and create the electrochemical gradient that powers the work done by the ATP synthase. The process by which this happens is outlined below (Scott, 2008). The *thylakoid lumen* is contained within the thylakoid membrane. It is a clear matrix in which proton concentrations build and drive the photosynthetic process (Scott, 2008).

Photosynthesis

The process of photosynthesis occurs within the chloroplast. The process occurs in two reactions that support one another. See Figure 24 for a high-level summary of the inputs and outputs of each reaction. A more granular look at each system opens the black boxes of both the light and dark reactions to support the application of the biomimetic lens in later analysis.

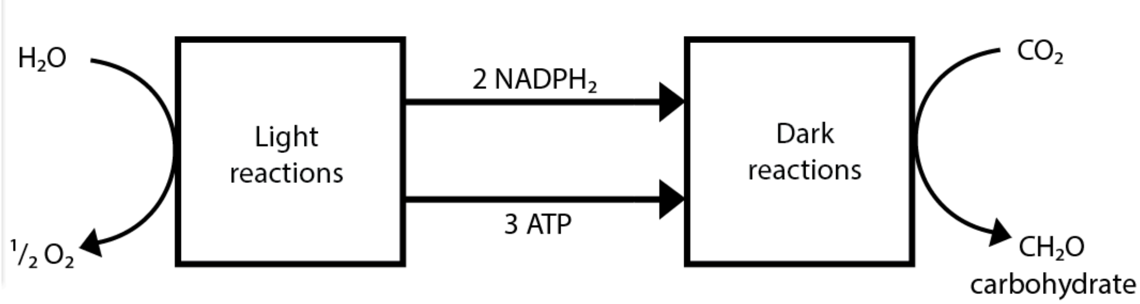


Figure 24. Reductive diagram of photosynthesis
(Hall, 1999, p. 79)

The 'light reaction' of photosynthesis occurs primarily within the thylakoid membrane with some action occurring in the stroma and thylakoid lumen adjacent to the thylakoid membrane. The light reaction begins when a photon makes it through the cuticle and epidermis (which will be discussed in further detail in the next section, "The leaf system") and is focused by the chlorophyll onto *Photosystem II*. This system absorbs photons whose energy drives the oxidation of water releasing protons into the lumen and donating the resulting electrons to the *plastoquinones PQ* (Hall, 1999). *Water* in the lumen is critical as it contains the electron that is excited and drives the rest of the photosynthetic process. It also releases the oxygen that is necessary for the functioning of the larger ecosystem (which will be discussed in later sections). The water in the lumen comes from the water uptake processes of other plant organs, which will be discussed later as well.

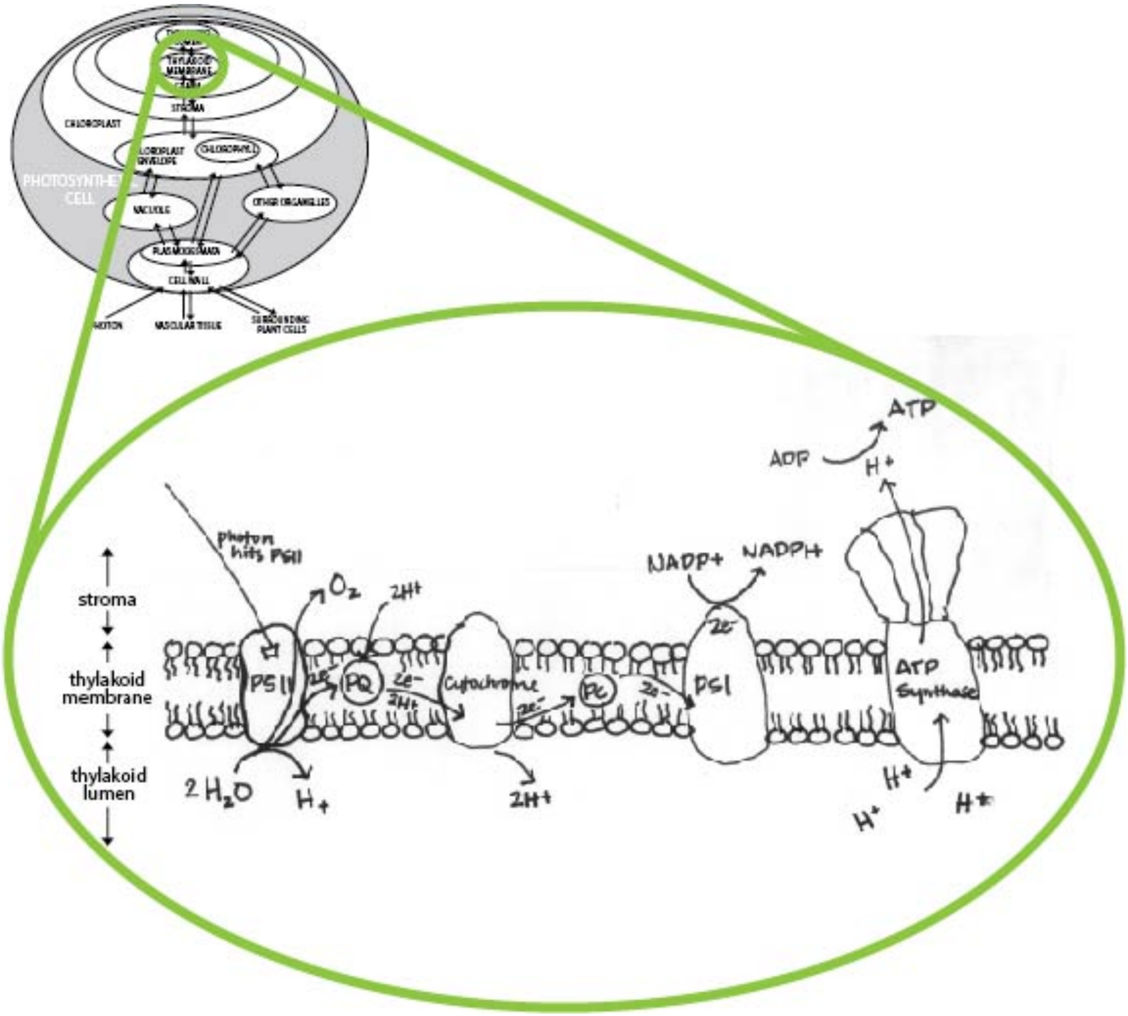


Figure 25. The light reaction of photosynthesis
Developed by author

Plastoquinones (PQ) is an abundant molecule in the thylakoid membrane of chloroplast and is used to shuttle electrons (e-) between Photosystem II and the cytochrome in the process driving the transport of protons (H+) from the stroma to the cytochrome (Hall, 1999). The cytochrome passes electrons from PQ to *plastocyanin* (PC) while donating the two protons that were picked up by PQ to the thylakoid lumen. This contributes to the build-up of protons in the lumen and the establishment of the electrochemical gradient. *Plastocyanin (PC)* is a protein that also exists within the thylakoid membrane and transports electrons between the cytochrome and Photosystem I (Hall, 1999). *Photosystem I (PS I)* absorbs a photon, which allows it to donate an electron to *NADP+* to create *NADPH*, which is essential to the function of the 'dark reaction' of photosynthesis (also referred to as the Calvin Cycle) (Hall, 1999). NADPH is a product of the PS I reaction in which PS I donates 2 electrons to NADP+. NADPH remains in the stroma where it is ready to become a part of the Calvin Cycle (it's role in which will be elaborated below) (Hall, 1999). An *electrochemical gradient* is established when the cytochrome and photosystem II are depositing protons in the lumen and PQ is drawing protons out of the stroma. When this gradient is established it drives the mechanics of the ATP synthase that transports protons from the lumen to the stroma to reconcile this gradient. *The ATP synthase* is the portal through which photosynthetic phosphorylation (the production of ATP) is made possible. The electrochemical gradient causes the ATP synthase to act similar to a water wheel – the energy of the flow of protons from the thylakoid lumen to the stroma is harnessed to synthesize ATP (Hall, 1999). *Adenosine diphosphate (ADP)* exists within the stroma. ADP is crucial to the formation of ATP and is the product of the formation of glucose. *Inorganic phosphate* (Pi) enters the chloroplast from the cytosol via the membrane transporter trios phosphate (Scott, 2008). *Adenosine triphosphate (ATP)* is formed in the stroma from ADP and Pi that is synthesized using the energy that results from the flow of protons across the electrochemical gradient created across the thylakoid membrane. It carries this energy to the Calvin Cycle where it is used to synthesize *glucose* (the major chemical product of photosynthesis).

The 'dark reaction' of photosynthesis, also known as the Calvin Cycle, does not require light directly, but relies on the products of the light reaction. The formation of ATP and the reduction of NADP to $NADPH_2$ are coupled, which indicates that the rate of flow of electrons to NADP is dependent on the presence of ADP and P_i (Hall, 1999). Together ATP and $NADPH_2$ become the "assimilatory power" that drives the reduction of CO2 into carbohydrate in the Calvin cycle (Hall, 1999). The primary role of the Calvin cycle is to "recycle [ATP and NADPH] compounds and at the same time to use the energy within the bonds of the molecules to make compounds that can accumulate and do not strain a plant's resources" (Scott, 2008, p. 26).

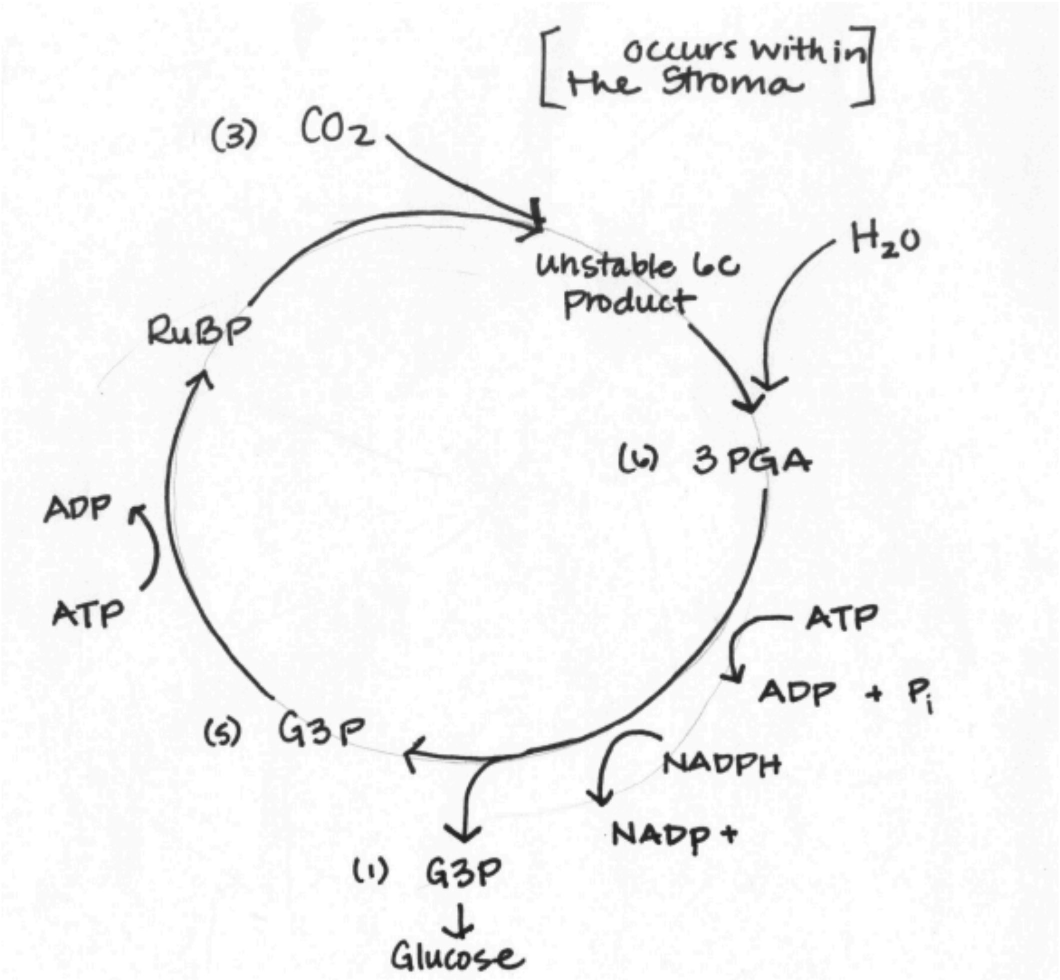


Figure 26. The dark reaction of photosynthesis (the Calvin Cycle)
Developed by author

The Calvin cycle requires two $NADPH_2$ molecules and three ATPs per CO_2 molecule (Hall, 1999). *Pi* enters the chloroplast from the cytosol via the membrane transporter trios phosphate (Scott, 2008). *RUBISCO* is the crucial protein for carbohydrate synthesis and only exists within the chloroplast. It is among the few known proteins that can transform inorganic carbon into organic material, and accounts for approximately 50% of all proteins in leaves (Scott, 2008). *Three-carbon phosphlorylated intermediate phosphoglyceric acid (3PGA)* is a three-carbon compound is formed by RUBISCO in the Calvin cycle. This compound is critical to the formation of sucrose – the transportable form of carbohydrate. The 3PGA exits the chloroplast during photosynthesis via the membrane transporter triose phosphate into the cytosol.

The result of photosynthesis is chemical energy in the form of carbohydrates including the two most important: *sucrose* and *starch*. *Sucrose* is a soluble disaccharide produced in the cytosol of photosynthetic cells and is the form carbohydrates take when needing to move around the plant (Scott, 2008). Because sucrose is soluble in water, it can easily flow throughout the plant to distribute chemical energy. Sucrose formation depends on the levels of 3PGA in the cytosol. High levels of phosphate prior to photosynthesis in the cytosol drive the phosphate translocator to transport 3PGA from the chloroplast to the cytosol and the phosphate from the cytosol to the chloroplast. Due to this, the first few hours of photosynthesis usually produce sucrose (Scott, 2008). When the concentration of sucrose in the cytosol exceeds its limit, it diffuses out of photosynthetic cells into heterotrophic tissues. In turn, concentrations of 3PGA begin to increase in the cytosol, its export from the chloroplast is halted, and photosynthetic productivity is focused instead on producing starch (Scott, 2008).

Starch is an insoluble carbohydrate that is synthesized within the stroma of the chloroplast during photosynthesis. An enzyme called starch synthase uses ADPglucose to combine into starch (Scott, 2008). Starch production begins after sucrose concentrations have exceeded their limits in the cytosol, continues throughout the rest of the day, and is stored in the leaves. Later, the starch is used in leaf metabolism overnight (Scott, 2008). It is estimated that 70% of starch remains in the leaf to support metabolism and the rest is exported to other areas of the plant. By the time the sun comes up the next day the starch levels have dropped and the cycle begins again.

5.2 The leaf system

The boundaries of the leaf system can be defined as every environmental element that interacts with the cuticle or lower epidermis and all internal elements sealed between the two reaching from the node to the tip of the leaf. The purpose of the leaf is to support the activity of the photosynthetic cells, which may include allowing more or less solar radiation, water, and other materials in or out of the leaf.

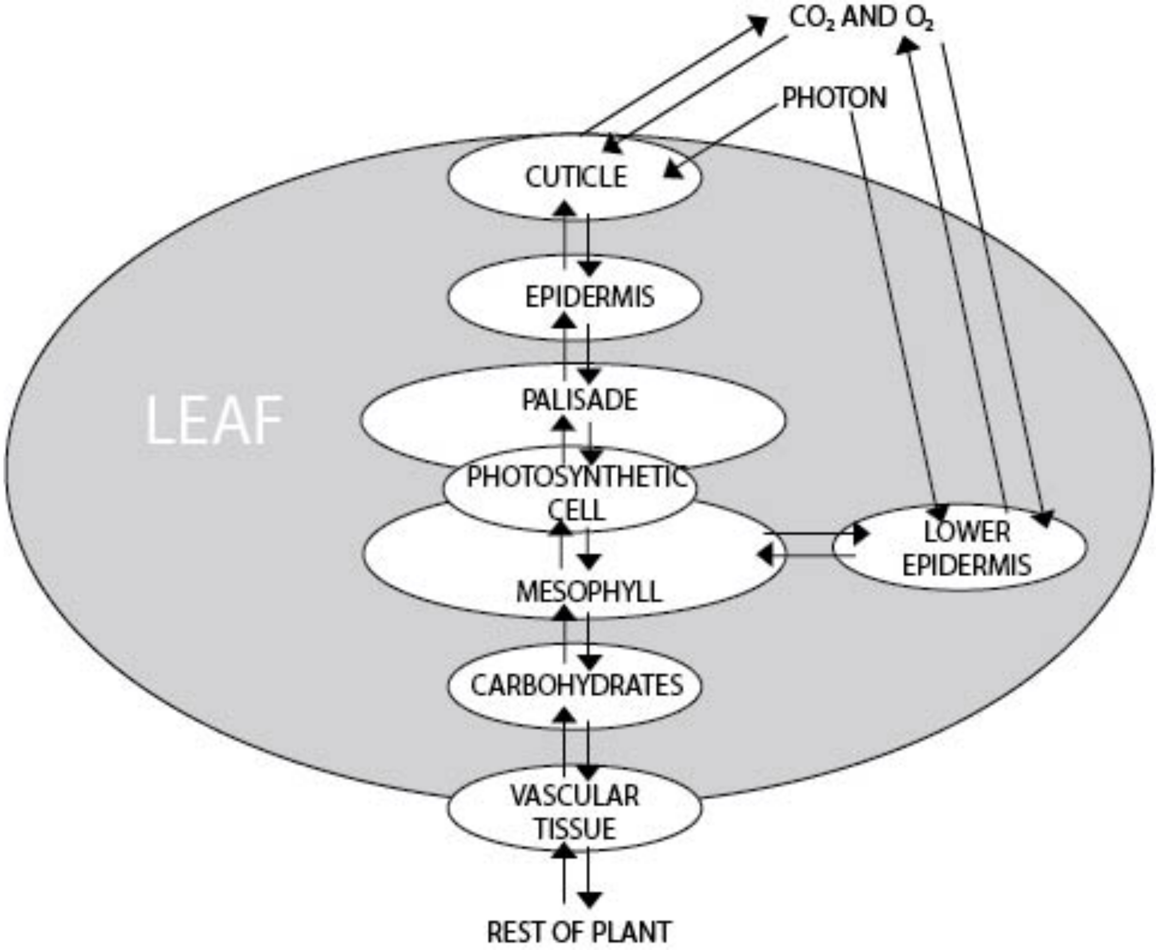


Figure 27. Leaf system map
Developed by author

Environmental elements

The external elements of the system include solar radiation, the surrounding air and any materials that are suspended in it, and the rest of the plant beyond the node connecting to the stem and subsequently to the whole plant. Incoming short wave radiation from the sun is the driving force of the function of the leaf (including photosynthesis, respiration, transpiration). Solar radiation interacts with the leaf in the form of *photons*. The role of the photon within the photosynthetic cell has already been described in the previous section, but this section will discuss how the photon arrives at the surface of the leaf and how it navigates its way to the photosynthetic cell to carry out photosynthesis. There are two major attributes of the element of sunlight that affect the function of the leaf: the *angle of incidence* and the intensity, or *irradiance*. The angle at which sun is hitting the surface of the earth, the angle of incidence, changes with time of day and time of year in a predictable and cyclical way. The angle of incidence is different for each unique latitude around the Earth. The latitude determines the angle at which the sun comes into contact with the surface of the earth and for how long the earth is exposed to solar radiation. The angle of incidence determines the total amount of solar radiation received daily, which in turn determines photosynthetic productivity. The intensity of sunlight, the irradiance, is the number of photons that are reaching the Earth, or the leaf, and is much less predictable. Though different regions experience patterns in weather, which in turn affect the irradiance at a point on Earth, it is not possible to predict what the irradiance will be on a particular day at a specific time. In addition to changing weather, the other ecosystem activity occurring – both human and non-human – can affect the amount of radiation reaching a particular point at a particular time. Irradiance is a function of both the angle of incidence and the composition of the air through which the radiation passes.

Photosynthesis including the production of chemical energy, the release of oxygen, the sequestration of carbon dioxide, and transpiration of water is highly dependent on the availability of sunlight. Only a small fraction of the total solar energy that reaches the earth's surface can be used in the photosynthetic process. This fraction of the light spectrum is known as photosynthetically active radiation (PAR) and consists of waves between 400 and 740mm (Smith & Smith, 2008).

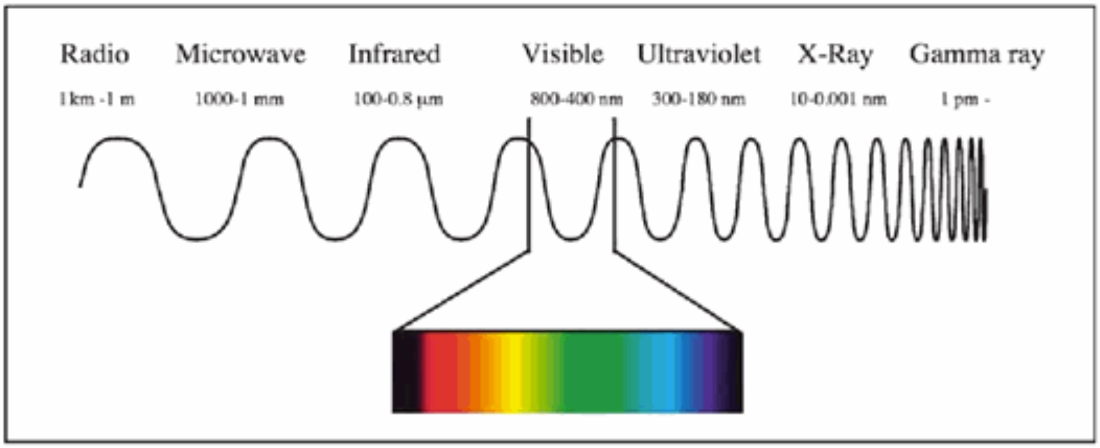


Figure 28. Composition of solar radiation
(Scott, 2008, p. 22)

The air surrounding the leaf can both inhibit or increase the amount of radiation reaching the leaf as well as trigger certain physical reactions within the plant itself. The surrounding air consists of many materials, however, there are four characteristics that are particularly important to the function of the leaf (photosynthesis). The availability of *carbon dioxide* (CO_2) can trigger certain plant behaviors. Plants both produce and uptake CO_2. Similarly, the current concentration of *oxygen*, *tsemperature* and *humidity* also impact the effectiveness of photosynthesis. The leaf is connected to the rest of the plant through the stem and the *vascular tissue* within it. The relationship between the autotrophic organ (the leaf) and the heterotrophic organs (the rest of the plant) is symbiotic. The details will be outlined further in the following section and will include the transport of energy from the autotrophic to heterotrophic organs and the transport of water and nutrients in the opposite direction.

Internal elements

The leaf itself consists generally of the photosynthetic cells, the infrastructure necessary for transporting materials, and the surrounding protective tissue. The overall leaf structure has been refined over the course of the evolution of the particular plant. The resulting shape, size, position relative to the sun, and the age of the leaf are largely determined in reaction to the solar characteristics of the environment. There are three underlying components of function that determine the shape and form of the leaf: they need to offer a wide area for the capture of light energy; they need to be thin for efficient light interception per unit of material and gas exchange for CO_2 fixation; and the means to transport the resulting carbohydrates to the heterotrophic tissues of the plant (Scott, 2008). However, "leaves come in so many varying shapes and forms that there is apparently no specific leaf shape which is optimal for photosynthesis" (Scott, 2008, p. 9). The position of the leaves in relation to external elements including the position of the sun, the air, and the availability of water and nutrients is interconnected the leaf's function. In diaheliotropism, a form of heliotropism, the leaf tracks the sun to keep the surface perpendicular to the light source throughout the day. Though it is known that organs connected to the leaf, called the pulvinus, controls the movements associated with diaheliotropism, the mechanism for their function is not understood (Scott, 2008).

Within the overall leaf structure, there are several types of cells playing different roles. First, there are *protective cells* in the cuticle, epidermis, and palisade. In most plants the *cuticle* is the first defensive barrier for the leaf. Although it is often transparent, letting the entire light spectrum pass, the cuticle is involved in limiting water loss as it responds to current environmental conditions, namely humidity levels. The *epidermis* is a secondary defensive barrier for the leaf. The epidermis plays a crucial role as a gatekeeper for sunlight coming into contact with the leaf – harmful UV-B rays are blocked while the light with wavelengths that drive photosynthesis is focused and directed to the chloroplasts. Additionally, the epidermis is the site of the *stomata*, which open and close in response to environmental conditions to control the amount of water and other gases that can both enter and exit the leaf (Smith & Smith, 2008). The *palisade* layer is comprised of vertically oriented cells with high concentrations of chloroplasts and is part of the inner mesophyll layer (Scott, 2008). In the center of the leaf is the *mesophyll*, which is also where photosynthetic cells are located. The photosynthetic cells are where photosynthetic activity takes place. These were described in detail in the previous section. The leaf both produces energy (in the photosynthetic cells) and expends energy as it metabolizes and grows.

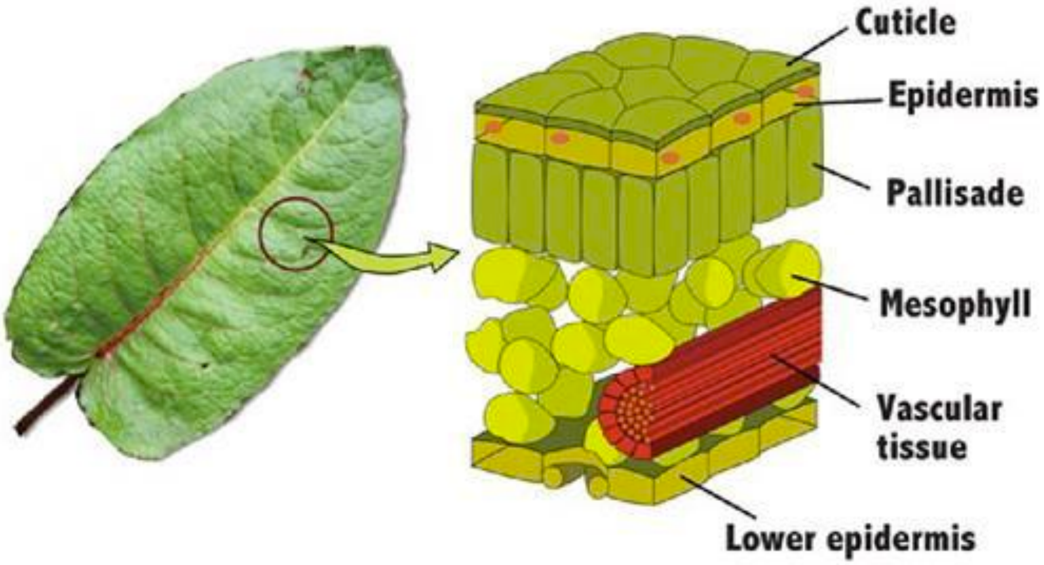


Figure 29. Leaf section
(Scott, 2008, p. 19)

Vascular tissue is the medium through which materials are passed through the plant in both directions. *Phloem* is the vascular tissue that transports both carbohydrates and amino acids throughout the plant. In the leaves, sucrose that is produced in the cytoplast of photosynthetic cells and diffuses through the apoplastic pathway to the phloem (Scott, 2008). In the leaf, the phloem consists of several types of cells including *sieve cells* that transport the materials, *companion cells* that are metabolically active, and *fibers* that reinforce and protect the other cells (Scott, 2008). Sucrose is drawn out of the leaf and into the phloem due to the metabolic activity of the companion cells. The phloem joins together to form wider pathways as it approaches the stem. The vascular tissue serves as the key node between the autotrophic leaf and the rest of the plant's heterotrophic organs. Heterotrophic organs include the stem, the roots, and the reproductive tissue all of which rely completely on the carbohydrates provided by the leaf through the vascular tissue to carry out all metabolic activity.

5.3 The plant system

For the purpose of this study, the plant system is defined as all plant organs and all environmental elements that physically interact with any of the plant organs. The function of the plant system is to coordinate the distribution of carbon, water, and nutrients appropriately to both sustain the life of the plant and drive reproduction to ensure the continuation of the species. The autotrophic organs (leaves) support the heterotrophic organs (the roots, stem, flowers, etc.) by supplying carbohydrates, and the heterotrophic organs support the production of those carbohydrates by regulating the uptake and allocation of water and nutrients. "In the integration of photosynthesis and respiration within the whole plant, the balance of carbon uptake and loss is a direct function of the relative contribution of these different tissues to the total mass of the plant" (Smith & Smith, 2008, p. 90).

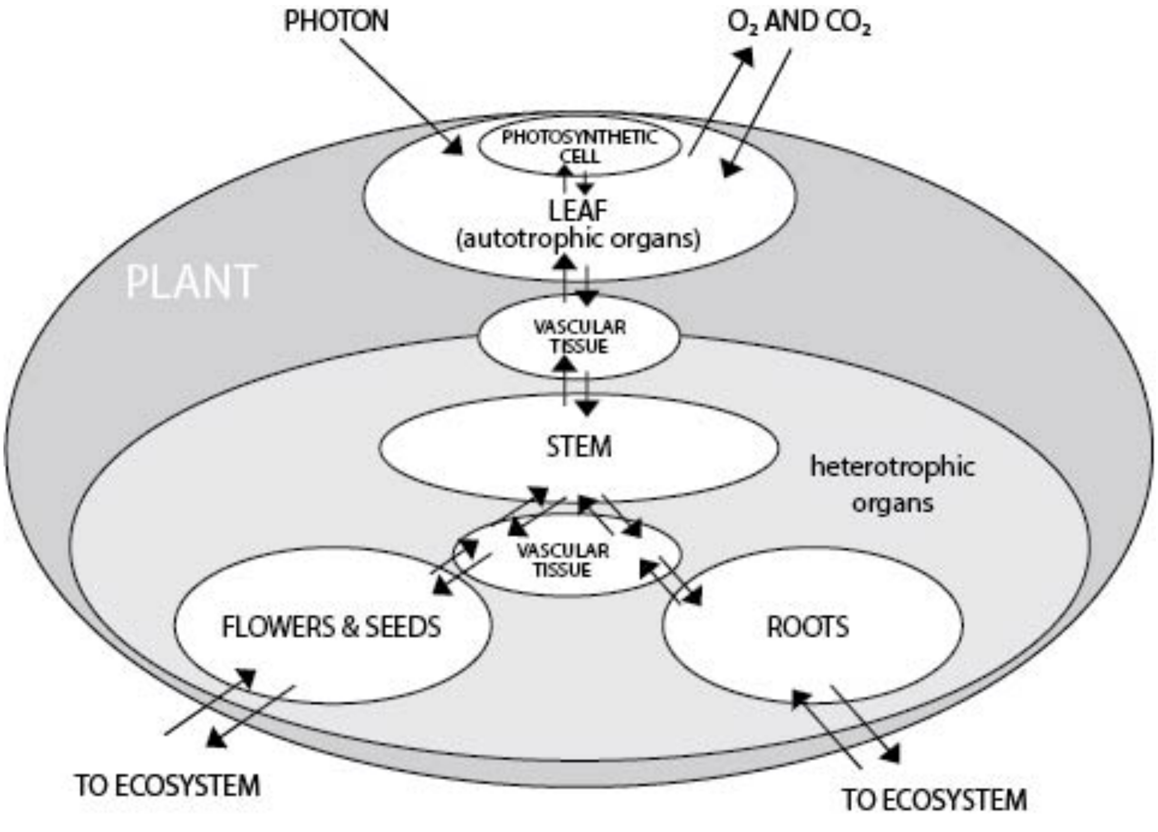


Figure 30. Plant System
Developed by author

Environmental elements

The environmental elements that interact directly with the plant system include the air and the sun, as explained in the previous sections, but also include soil and the water, nutrients, and other materials found within the soil.

Internal elements

The internal elements of the plant system include all plant organs, both autotrophic energy-producing organs and heterotrophic energy-consuming organs. The elements and attributes of the leaf system, the *autotrophic organs*, were discussed in the previous section. *Vascular tissue* is the medium through which all materials are passed through the plant in both directions. *Phloem* in the leaves was discussed in the previous section, however phloem can be found in other parts of the plant as well. The phloem that is dispersed throughout the leaves meets at the stem and is bundled before it connects to the rest of the plant. *Xylem* can be found in the roots and stem and is the medium through which water and nutrients flow from the soil to the rest of the plant. Water moves up the plant through two processes: increased pressure in the roots pushing the water upward and negative pressure in the leaves due to transpiration pulling the water upward (Scott, 2008). Like the photosynthetic process, the sun also drives this process as it causes transpiration.

Energy flows through the vascular tissue in the form of *carbohydrates*:

> Plants budget this fixed energy or net income for different uses. A portion is allocated to growth, the build up of components such as stems and leaves that promote the further acquisition of energy and nutrients. A portion goes to storage, which is photosynthetic built up in the plant for future growth (Smith & Smith, 2008, p. 408).

Carbohydrates are distributed throughout the plant depending on its age and the current environmental conditions. In ideal conditions, the most productive way to spend chemical energy is to invest in the further growth of leaf tissue to promote increase the photosynthetic surface therefore increasing productivity. However, each type of plant organ plays a critical role in collecting and delivering the resources necessary to photosynthesis. The net gain of carbon is a function of the average rate of photosynthesis, the total photosynthetic surface area, and the rate of carbon loss due to transpiration, which is determined by the total mass of living tissue (Smith & Smith, 2008).

To ensure immediate growth, carbohydrates must be allocated to leaf tissue to increase photosynthetic surface area. To ensure medium-term growth more carbon must be allocated to stems to increase reach and stability and to the roots to ensure access to resources. In mature plants, carbon must be allocated to the production of seeds and flowers to ensure the long-term growth and survival of the species.

Ecosystem	**Plant types**	**Root to Shoot Ratio**
Tundra	Sedge/grass meadows	Ranges 5 to 11
	Shrubs	Ranges 4 to 10
Prairie	Grasses	3
Forest	Trees	0.213
	Shrubs	0.5
	Herbs	1

Table 07. Allocation of carbon by ecosystem and plant type
Proportionate allocation of net primary production to below-ground and above-ground biomass (Smith & Smith, 2008, p. 490).

The *heterotrophic organs* within the plant include every part of the plant outside the photosynthetic leaves such as the root system, the stem, and reproductive tissues. These are deemed "heterotrophic" because they utilize the chemical energy created via the photosynthetic process, but do not contribute to the production of energy themselves. When the carbohydrate enters the cells of heterotrophic organs it can be used in three ways: respiration, storage, and growth.

The *root system* is a subsystem of the plant system. The function of the root system is to anchor the plant as well as to uptake water and minerals. There are two general types of roots – with many variations – that determine the overall structure of the root system. *Taproots* are characterized by a single primary root that tapers from the top down. *Fibrous roots* consist of many roots equal in diameter that lie in the shallow soil and whose width exceeds its depth (Scott, 2008). Elements within this subsystem include the *apical meristem* that controls the development of root growth and root hairs that assist in the uptake of water and nutrients (Scott, 2008). Roots can also be a vital storage space for carbohydrates in less than desirable above grade environmental conditions that will be needed for rapid growth in the future (Scott, 2008). The depth and width of roots is a function of both the availability of resources in the local environmental conditions and the size of above grade plant. Although some uptake of water by the roots does occur via capillary action, often the roots will actually move toward the resources it is attempting to acquire (Scott, 2008). *Root hairs* are critical to the function of the root because they greatly increase the surface area of roots.

The *stem* is the link between the root system and the autotrophic leaves and can vary greatly in length, width, and shape. The main function of the stem is to transport products of photosynthesis from the leaf to heterotrophic organs and transport water and nutrients from the root system to the leaves. Nodes are the points at which each individual leaf connects to the central stem. The internode is the spacing between nodes along the length of the stem: "Short internodes yield a plant which is short and produces a rosette of leaves. Longer internodes yield a plant which is tall and can take advantage of light at several different levels" (Scott, 2008, p. 9).

Plants can reproduce either asexually or sexually. In asexual reproduction, cells are essentially cloned with little to no room for genetic variation. In sexual reproduction, there is often cross-pollination, which allows for genetic diversity. In plants, flowers are the main organs involved in sexual reproduction. Although it is possible for the pollen from a flower to fertilize its own stigma, it has been observed since Charles Darwin's time that plants have evolved to prevent flowers from self-pollinating by physically separating the anther and the stigmata (Scott, 2008). Cross-pollination generally occurs in one of two ways: wind/water or animal transport (Scott, 2008). The production and distribution of seeds is nature's answer to the three major problems facing plants: immobility, longevity, and genetic variation (Scott, 2008). Often, the seed dispersal process begins with a gravity-mediated departure from the plant. Then, similar to mediums for cross-pollination, seed distribution can be carried out by wind, water, or animal transport throughout the ecosystem.

5.4 The ecosystem

In this case, the boundaries of the photosynthetic community are defined via Smith and Smith's broad understanding of community: "a collection of plant and animal populations interacting directly or indirectly" (Smith & Smith, 2008, p. 383). An ecosystem includes inorganic matter as well. The ecosystem is made up of three basic structural components: autotrophs, heterotrophs and inorganic or dead organic matter (Smith & Smith, 2008). The function of the system is to sustain life.

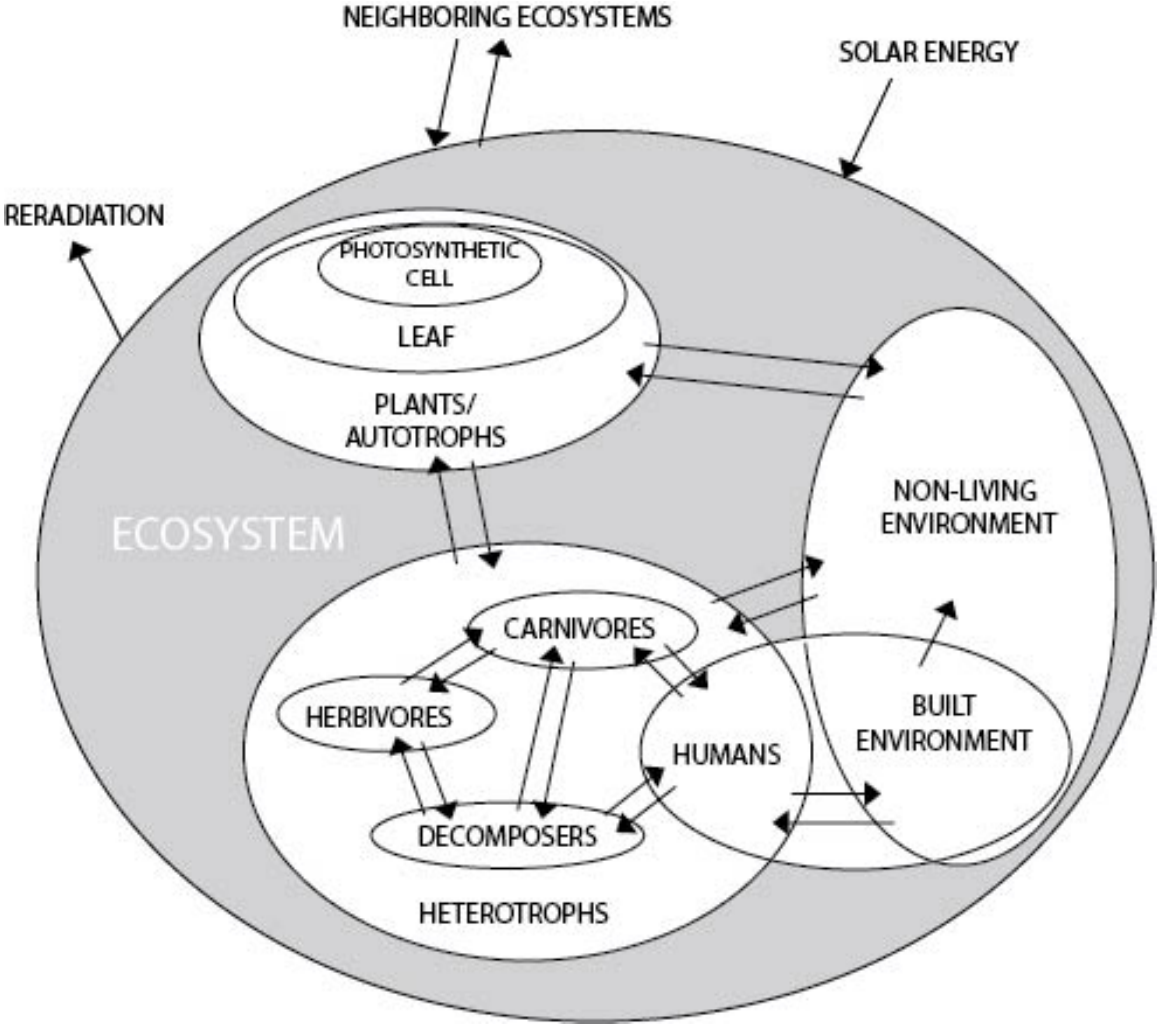


Figure 31. Ecosystem map
Developed by author

Environmental elements

The boundaries of ecosystems are often difficult to define since, according to Smith and Smith, "most ecosystems…possess no distinct boundaries… boundaries described in most cases are arbitrary subdivisions of a continuous gradation of communities" (Smith & Smith, 2008, p. 480). The divide between communities is not necessarily natural, although it might be based on natural characteristics, but instead communities are defined as a way to better understand and conceptualize intercommunity dynamics.

The importance of solar energy has already been emphasized in the systems of small scales, but it is critical to revisit its importance as it relates to the ecosystem as a whole. Smith and Smith frame the role of solar energy in the ecosystem:

> The driving force of the system is the energy of the sun, which causes all other inputs to circulate through the system. Outflows from one subsystem become inflows to another. Whereas energy is used and dissipated as heat of respiration, the chemical elements from the environment are being recycled. Consumers regulate the speed at which nutrients recycled through the system (Smith & Smith, 2008, p. 480).

The amount and distribution of sunlight throughout the community is dependent on the characteristics and interactions of internal elements.

Internal elements

The designation of groups of like biological elements as *species* is important to the understanding of ecosystems. However, the definition of what constitutes a species is contested – an example of the social construction of scientific knowledge. In the most basic sense, a species can be defined as "all of the organisms that are potentially capable of interbreeding under natural conditions" (Perlman & Milder, 2004, p. 74). However, in practice, identifying the divide between one species and another is more difficult considering the constant evolution of organisms and their interconnections. In addition to distinguishing between groups of organisms based on reproductive patterns and genes, groups can be distinguished based on geography. The term *population* describes "a group of individuals of a single species that all live in the same place and that are at least somewhat isolated or distinct from other populations" (Perlman & Milder, 2004, p. 74). The collection of populations of many species cohabiting a single place is referred to as a *community* among ecologists. When non-living elements of the place are also included, it is referred to as an *ecosystem* (Perlman &

Milder, 2004). Non-living elements include soil, nutrients, water, and air. *Water* enters and exits the system in a number of ways including precipitation, ground water, run off, and evapotranspiration. The fluid nature allows for water to enter and exit the system fairly easily. This fluidity affects the quantity and quality of water in the system. Similar to water, the fluid nature of *air* also allows for constant entering and exiting of the system resulting in fluctuating air composition. Dissimilar from fluids like water and air, *soil* does not often enter or exit an ecosystem on a short-term basis. Although soil often does not leave the system on a short-term basis, its characteristics can change through its interactions with water, air, and biologic elements of the system. In addition to the physical organic and inorganic elements of the system, there are also intangible elements, namely energy and information that move throughout the ecosystem. There are many ways to describe the characteristics of ecosystems based on the organisms in habiting the ecosystem, its physical structure, and the relationship between various organisms with each other and with their environment.

Autotrophs within the ecosystem are “the energy-capturing base of the system” (Smith & Smith, 2008, p. 479). There are several methods for characterizing the autotrophic plant population of an ecosystem. The vertical structure of an ecosystem refers to the layers of plant types of various sizes, branching patterns, and leaf types (Smith & Smith, 2008). Each layer – canopy, understory, shrub, herb/ground, and floor – has distinct characteristics within the community and layers at the same level can differ from community to community. The characteristics of the canopy, the highest layer in the vertical structure of ecosystems, typically determine the functioning of the lower layers. An open canopy will allow for the development of a rich understory so long as water and nutrients are available, whereas a dense canopy will inhibit the growth of the understory (Smith & Smith, 2008). There is also a strong positive correlation between the number of vertical layers within an ecosystem and the diversity of animal life. The diversity of layers within an ecosystem allows the support of a diverse group of species with distinct niches (Smith & Smith, 2008). There is diversity not only vertically throughout the ecosystem, but also across the landscape. The *horizontal structure* of an ecosystem refers to the variation in density and species make-up across the landscape. Changes in horizontal structure are characterized by soil structure, soil fertility, moisture conditions, slope, and light distribution (Smith & Smith, 2008). Similar to vertical stratification, horizontal structure also affects the types and number of species that can be supported within an ecosystem.

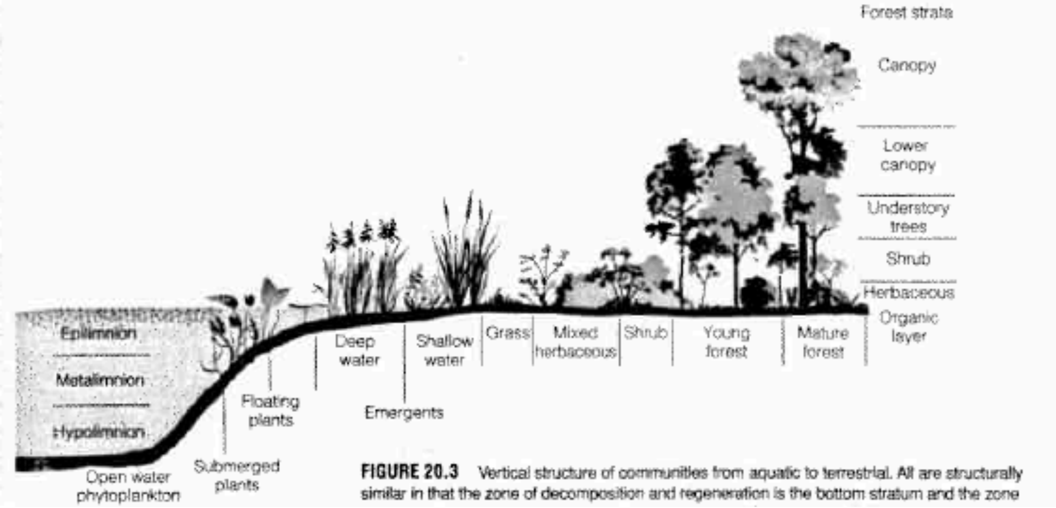


Figure 32. Vertical structure
(Smith & Smith, 2008, p. 385)

The horizontal and vertical structure describes the overall organization of the ecosystem whereas terms such as *species diversity*, which is a function of *species richness* and *evenness*, describe the biologic elements that exist within that organization. *Species richness* describes the count of each species while evenness depends on the equitable distribution of multiple species (Smith & Smith, 2008). Biological elements within the ecosystem that make up the species covered by species diversity include both *autotrophs* (plants described in the previous section) and *heterotrophs*. By definition, heterotrophs "utilize the food stored by the autotrophs, rearrange it into other organic compounds, and finally decompose the complex materials into simple, inorganic substances. In this role they influence the rate of energy and nutrient flow through the ecosystem" (Smith & Smith, 2008, p. 479).

Relationship	Key elements involved
Competition	**Individual** v. **individual** of **same or similar species** based on availability of **non-living resources**
Predation	**Carnivore** v. **herbivore**
Herbivory	**Herbivore** v. **autotrophic plant**
Parasitism	**Individual** v. **individual**
Mutualism (Cooperation)	**Individual** and **individual** based on larger ecosystem function

Table 08. Types of species interactions
Developed by author

There are many ways the diverse biological elements within a single ecosystem can interrelate to one another including competition, predation, and cooperation. *Competition* is critical to shaping communities (Smith & Smith, 2008). Competition can occur around many different factors within an ecosystem including but not limited to the availability of light, water, nutrients, and space; and it is heavily dependent on the likeness of the species within the system (Smith & Smith, 2008) (Perlman & Milder, 2004). The level of competition may vary by time of year or long-term weather patterns affecting the limiting factors. Competition provides bottom-up control of populations within an ecosystem whereas predation is recognized as top-down control.

Smith and Smith link competition and *predation* in their description of community dynamics: "within a community, carnivores compete strongly among themselves and severely exploit their resources. Herbivores are regulated by predators and have little impact on vegetation." (Smith & Smith, 2008, p. 383). In predation, one organism acquires energy by consuming the tissues of another. The effect of the predator-prey relationship on community structure is often easier to articulate than that of competition especially when illustrated in a food web. Predation can happen between carnivores and herbivores or herbivores and autotrophic plants, known as *herbivory*. Unlike predation, in herbivory, the organism only consumes portions of the other without killing it (Perlman & Milder, 2004).

Cooperation between species through *mutualism* is often overlooked, according to Smith and Smith, and can be more significant than competition or predation in some ecosystems (Smith & Smith, 2008). Mutualism is "an interaction between two species in which both species benefit" (Perlman & Milder, 2004, p. 85). Examples of mutualism include pollinator-plant relationships (Perlman & Milder, 2004) (Smith & Smith, 2008). Although mutualism supports ecosystem function in ways that are difficult to predict, the relationships between cooperating species can make ecosystems vulnerable.

Overall, the larger biological system involved in the photosynthetic productivity of an ecosystem has many complex interactions with environmental elements and between internal elements. These interactions have been refined over millions of years, and there are many aspects of the interactions and the system functioning as a whole that merit mimicry in the design of systems of energy production. In the next chapter, I will look specifically at the intricacies of the limited current conventional photovoltaic system in preparation for applying the lessons learned in this chapter.

6 MECHANICS OF THE CONVENTIONAL PHOTOVOLTAIC

This chapter will include a detailed description of the systems involved in production of electricity using current conventional crystalline silicon photovoltaics including the elements of the systems, their interconnections to one another and their interconnection with the purpose of the overall system. Similar to the previous chapter, this investigation will study four progressively complex systems at four distinct but interconnected scales: the photovoltaic cell, the photovoltaic panel (or module), the photovoltaic array, and the photovoltaic community. These systems differ in scale and in purpose, progressing from energy production to energy consumption to energy distribution.

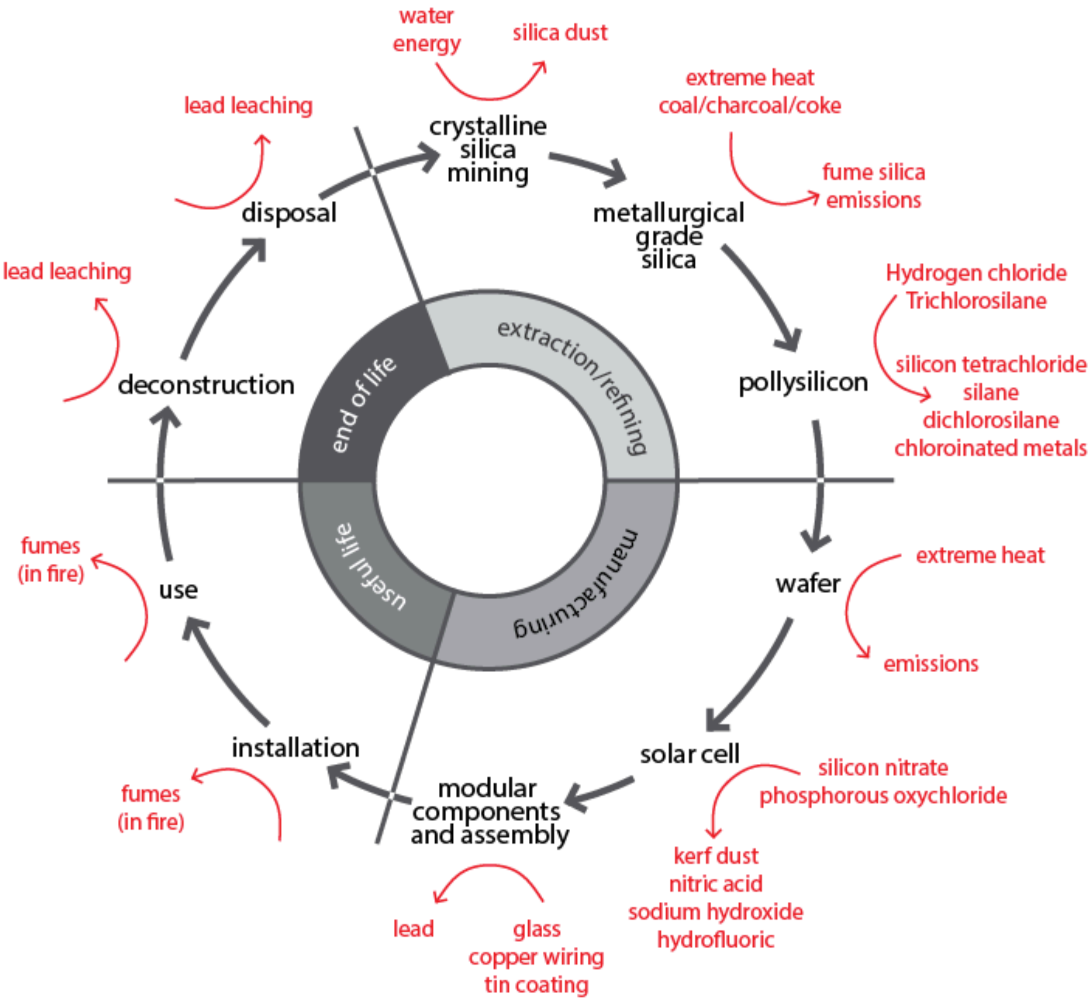


Figure 33. The lifecycle of the photovoltaic system
Developed by author based on content from Good Company

Also similarly to the photosynthetic system explored in the previous chapter, the photovoltaic system can be studied across both scales and time. However, unlike plant-related systems, photovoltaic systems are not inherently cyclical. Though there is the potential for recycling, there is not a clear cyclical path for materials and energy to follow. This chapter primarily focuses on the functioning of the system across scales at during the “useful life” period in the lifecycle of the PV system as seen in Figure 33.

6.1 Photovoltaic Cell

The boundaries of the photovoltaic cell system can be defined as the crystalline silicon wafers and the photons that interact with its surface. It is by necessity that there are no other environmental elements interacting with the photovoltaic cell seeing as the materials are highly sensitive to most environmental conditions. The purpose of the photovoltaic cell system is to generate electric current.

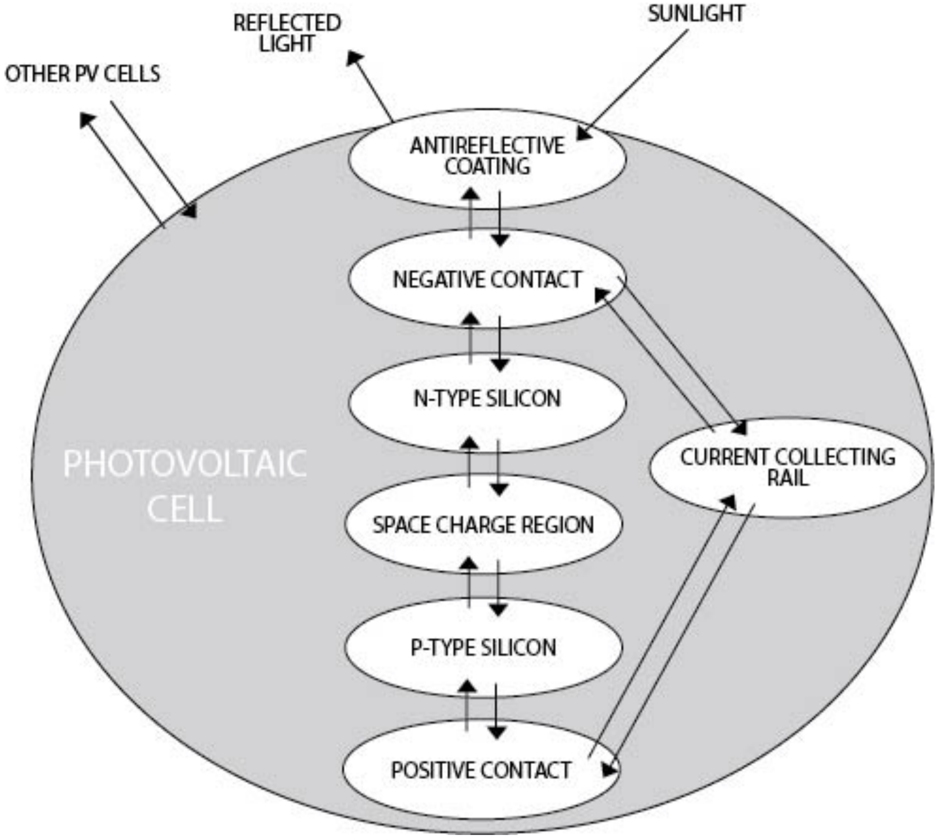


Figure 34. Photovoltaic cell system
Developed by author

Environmental elements

Due to the sensitive nature of the materials used in photovoltaic cells, by design the only environmental element that photovoltaic cells interact with is solar energy in the form of *photons*. A photon's interaction with the silicon wafer drives the photovoltaic process that will be described throughout this chapter. Photons arrive at the photovoltaic cell either as direct or indirect (diffuse) light. The energy level of direct radiation is greater, therefore more likely to elicit the photovoltaic effect. However, in many situations diffuse light can also initiate the effect or, when beneficial, photovoltaics can be specifically designed to respond to lower energy solar radiation.

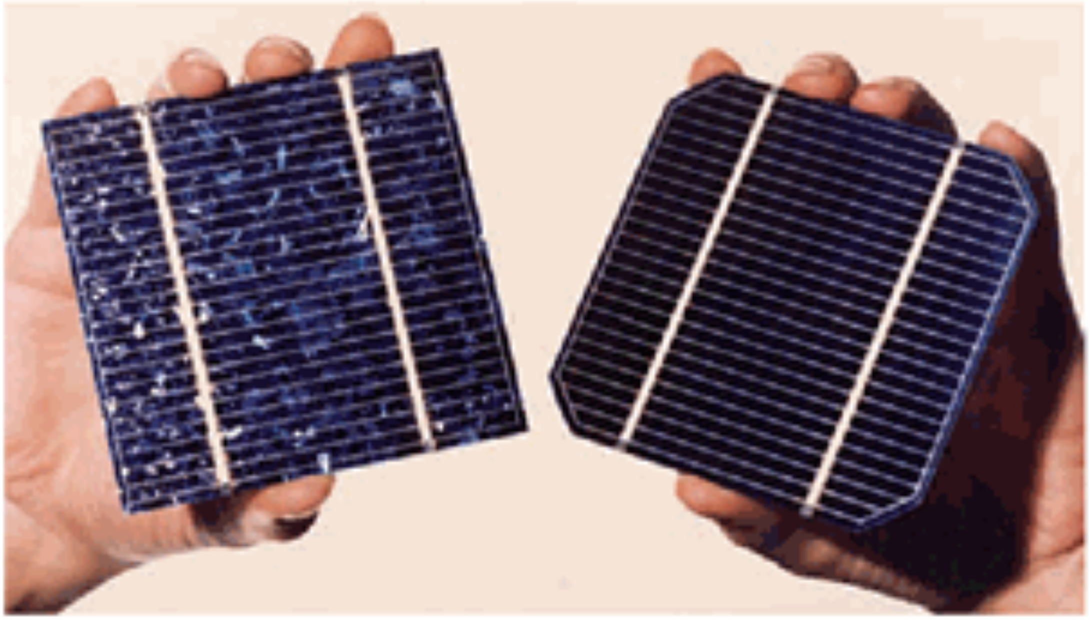


Figure 35. Crystalline photovoltaic cells
(Häberlin, 2013, p. 89)

Internal elements

As suggested by its name, crystalline silicon consists of atoms in a lattice structure with fixed connections, known as crystals. This structure occurs as a result of the individual silicon atoms that have four valence electrons and therefore seek to acquire (or share) four electrons with another atom (Mertens, 2013). Crystalline silicon photovoltaic cells, however, are not made of pure silicon crystal. In order to maximize the performance of the semiconductor, a p-n junction is created by doping one layer of silicon crystal with an atom with one more valence electron than silicon (n-doping) and another layer with one atom with one less valence electron than silicon (p-doping).

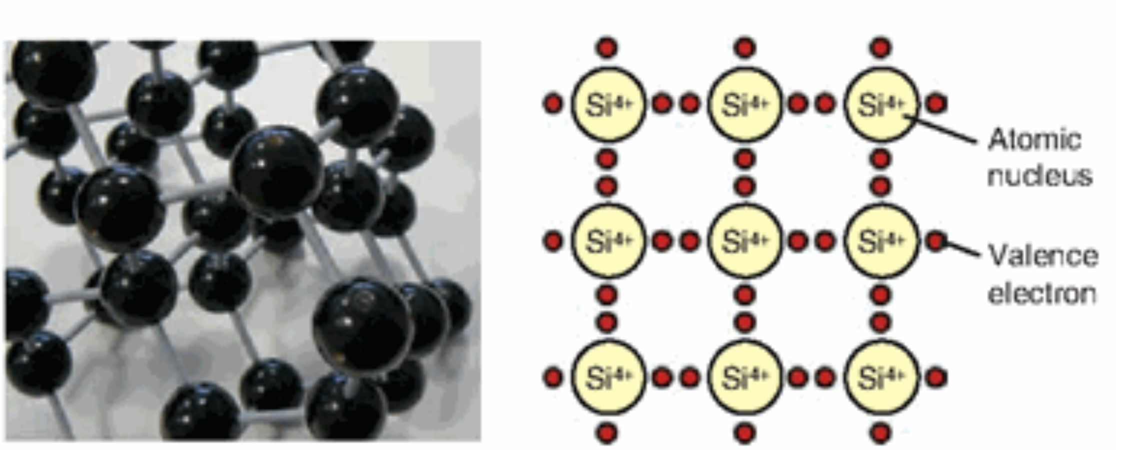


Figure 36. The molecular structure of crystalline silicon
“Structure of a silicon crystal: The left-hand figure shows the spherical model and the right the two-dimensional depiction” (Mertens, 46).

The *p-n junction* is the space between the n-type silicon and p-type silicon in which electrons are exchanged and electric current is made possible. In *n-type silicon* (n-emitter), when an atom with one greater electron is exposed to the silicon crystal lattice, the atom falls into place in the lattice. Four electrons are in fixed bonds with neighboring silicon atoms, but one electron finds no open bond and is very weakly connected to the nucleus. This makes the fifth electron a free electron at room temperature (Mertens, 2013). *P-type silicon* (p-base) is the layer of silicon crystal that includes atoms with one less valence electron than the silicon atoms. The doping atoms fall into place in the crystal lattice, but leave an electron hole in their bonds with neighboring silicon atoms (Mertens, 2013). The structures of both types of doped silicon are illustrated on the following page in Figures 37 and 38.

The *bandgap* of a semiconductor describes the amount of energy that is needed to move an electron out of the valence band and into the conduction band (Mertens, 2013). This is important in photovoltaics because it will determine whether or not the energy from solar radiation is sufficient to transfer electrons to the conduction band in order to generate an electric current.

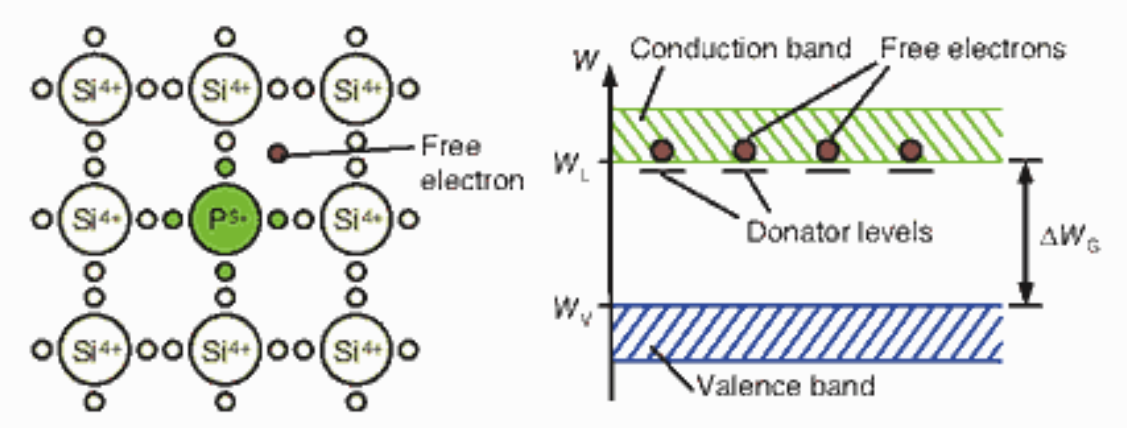


Figure 37. Molecular structure of N-type silicon
n-doping of semiconductors; one of the five valence electrons of the phosphorous atom is not necessary for the bond and is therefore available as a free electron. Because of the doping there is a new energy level in the band diagram, just below the conduction band edge (Mertens, 2013, p. 54).

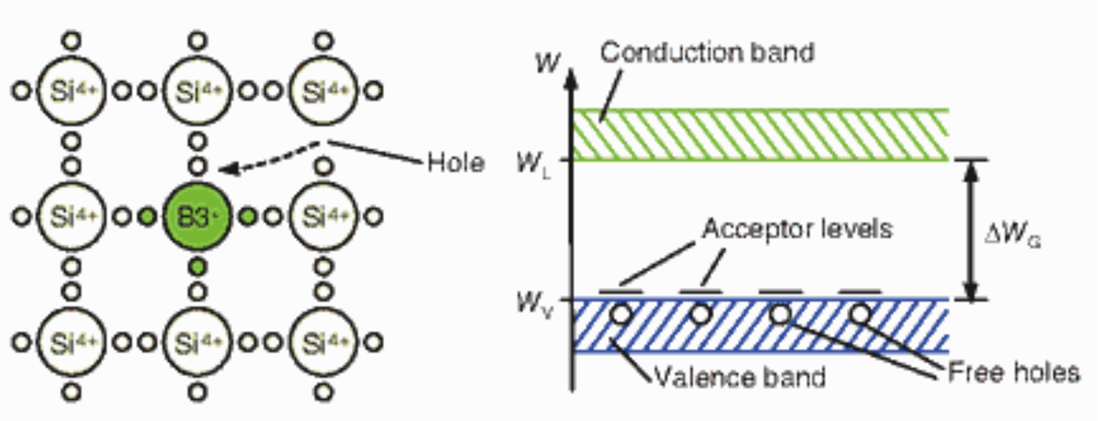


Figure 38. Molecular structure of P-type silicon
Example of p-doping of a silicon crystal with a boron atom; one of the four links remains open as the boron atom can only offer three valence electrons. A neighboring electron moves into this binding and thus 'generates' a hole (Mertens, 2013, p. 54).

The *space charge region* is where the photons with effective energy levels are absorbed. Electrons move toward the n-emitter and the negative contact and protons move toward the p-base and the positive contact (Mertens, 2013). There are two contacts that facilitate the electric charge. The *back contact* is the positive contact. This is a metal surface that acts as both support for the cell and a means of conducting electric current. The *front* *contact* is the negative contact. This is a metal grid that allows light to penetrate the cell through the gaps, but it continuous to collect excited electrons and channel them into the current collector rail to capture the energy of the electric current. The *current collector rail* (bus bar) is where the electric current is captured. It is metal and connects the back and front contacts, and allows excited electrons attracted by the overall negative n-type silicon to return to fill the holes left in the p-type silicon through the back contact (Mertens, 2013).

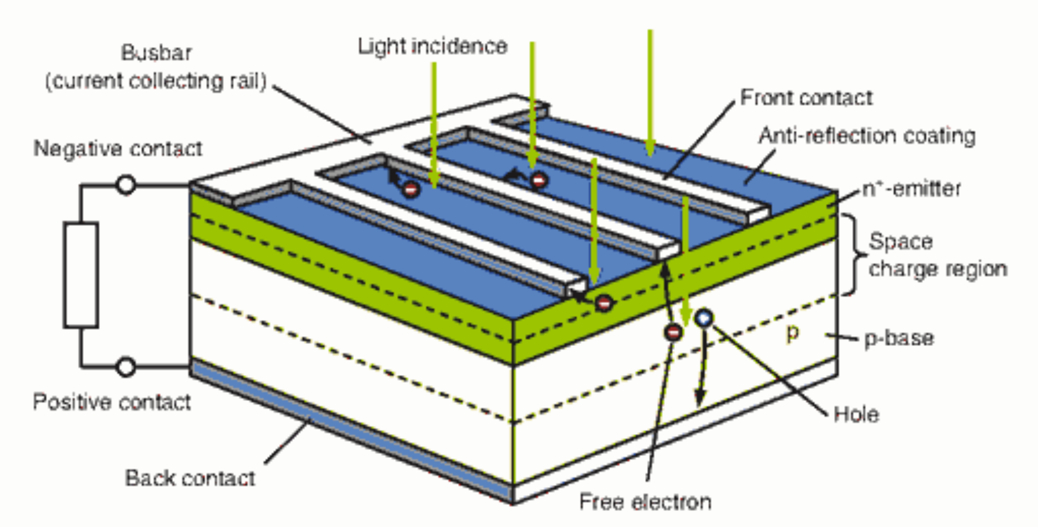


Figure 39. Photovoltaic cell in section
(Mertens, 2013, p. 70)

Anti-reflection coating increases the amount of light that is absorbed by the photovoltaic cell therefore increasing the potential for electric current to be generated. Presently silicon nitride, with a reflection factor of less than 1%, is the most common and most effective available material for anti-reflective coating in solar cells (Mertens, 2013). However, reflective coatings only work at one wavelength. The cell is then connected to other cells and to the larger panel system through direct current (DC) wiring. This node connects the PV cell system to the larger module system discussed in the following section of this chapter.

6.2 Photovoltaic modules

Photovoltaic cells are arranged within larger units referred to as photovoltaic modules. For the purposes of this study, the photovoltaic module system consists of the system of electricity-generating photovoltaic cells, the materials encasing the cells, and the external elements that the encasing protects the cells against. The purpose of this system is to support and protect the electricity-generating technology as well as make scalable installations possible.

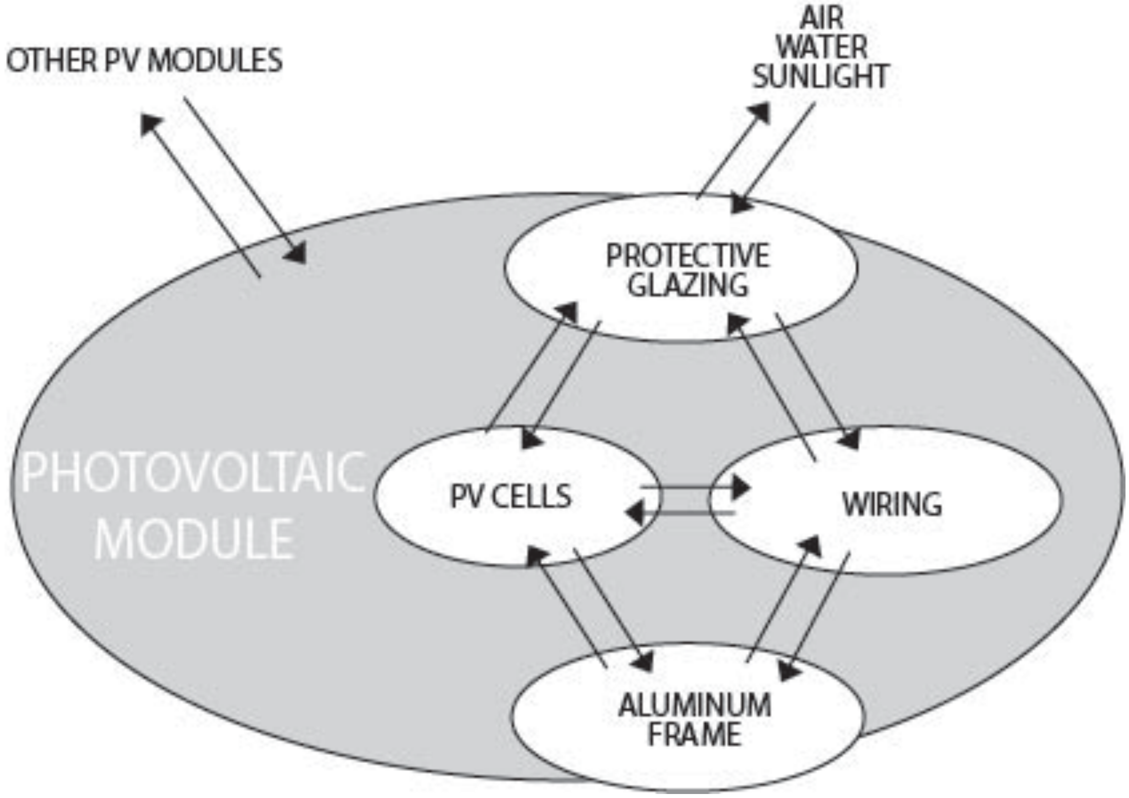


Figure 40. Photovoltaic module system
Developed by author

Environmental elements

The natural external elements that interact with the photovoltaic module include solar radiation, air, and water. Neighboring modules also interact with each PV module, but in large part, by design the number of neighboring panels does not affect the functioning of the single module, however the way in which the panels are connected does determine the voltage and amperage of the whole array (the scale that will be discussed in the next section). During the functional life of the PV humans need not interact with the modules themselves in order for them to function, in theory. However, in time periods outside the useful life as well as in isolated incidents of maintenance, humans also interact directly with the module as a steward of its purpose.

As discussed in the previous section, the intensity of solar radiation is the main determinant of the productivity of the photovoltaic module. However, it is also important to understand how the availability of solar radiation to each cell affects the module as a whole. The percent of a module that is shaded is *not* proportional to the loss in efficiency. Obstructing solar radiation from just one of the 36-72 cells found in typical photovoltaic module can result in a loss of module efficiency of 75% (Solar Energy International, 2007). At the module scale, solar radiation interacts most directly with the protective glazing. The relationship between solar radiation and the most common glazing types used in this application will be discussed in the glazing portion of this section.

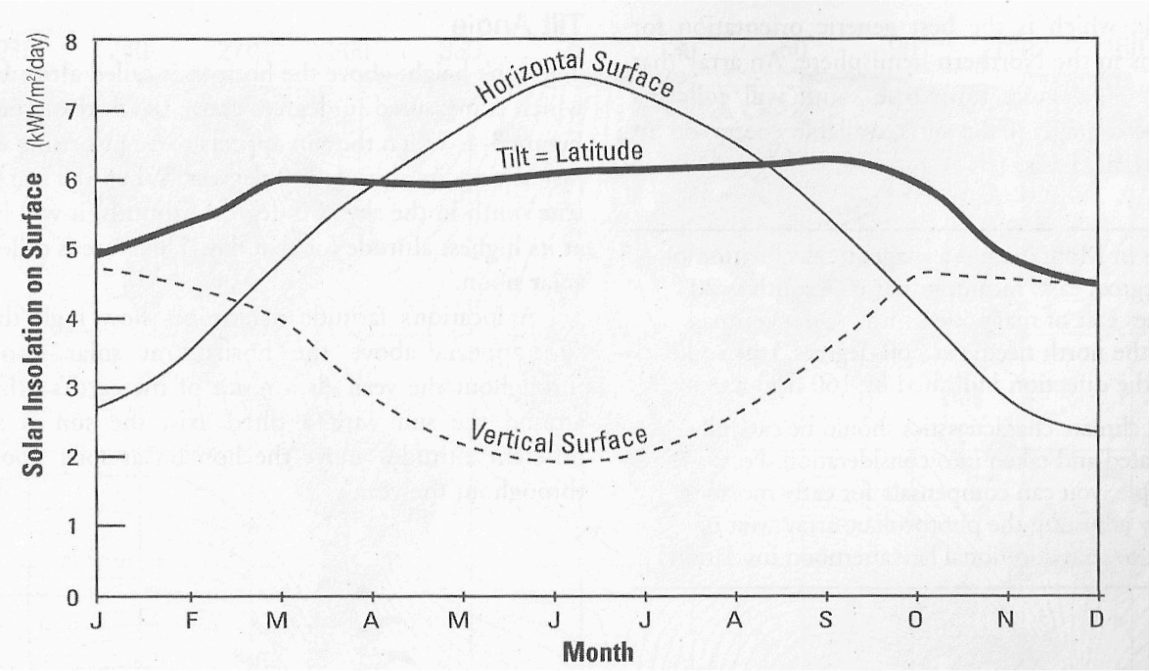


Figure 41. Effects of array tilt on energy production
(Solar Energy International, 2007, p. 34)

Crystalline silicon can be sensitive to natural elements, and the module components are meant to protect the cells from these elements. Cell temperatures above 77° Fahrenheit (25° Celsius) directly affect the productivity of the PV module. On average, for every degree the cell temperature rises above 77° F the module voltage decreases by approximately 0.5%

resulting in lower power outputs (Solar Energy International, 2007). The purpose of the module is to protect the electricity-generating PV cells to avoid undesirable conditions that will deter productivity. Modules that are designed and installed to allow ample air flow around the surfaces often effectively limit efficiency losses due to overheating of PV cells. Other modules choose glazing or framing material with lower heating coefficients to reduce the effects of overheating the cells (Solar Energy International, 2007).

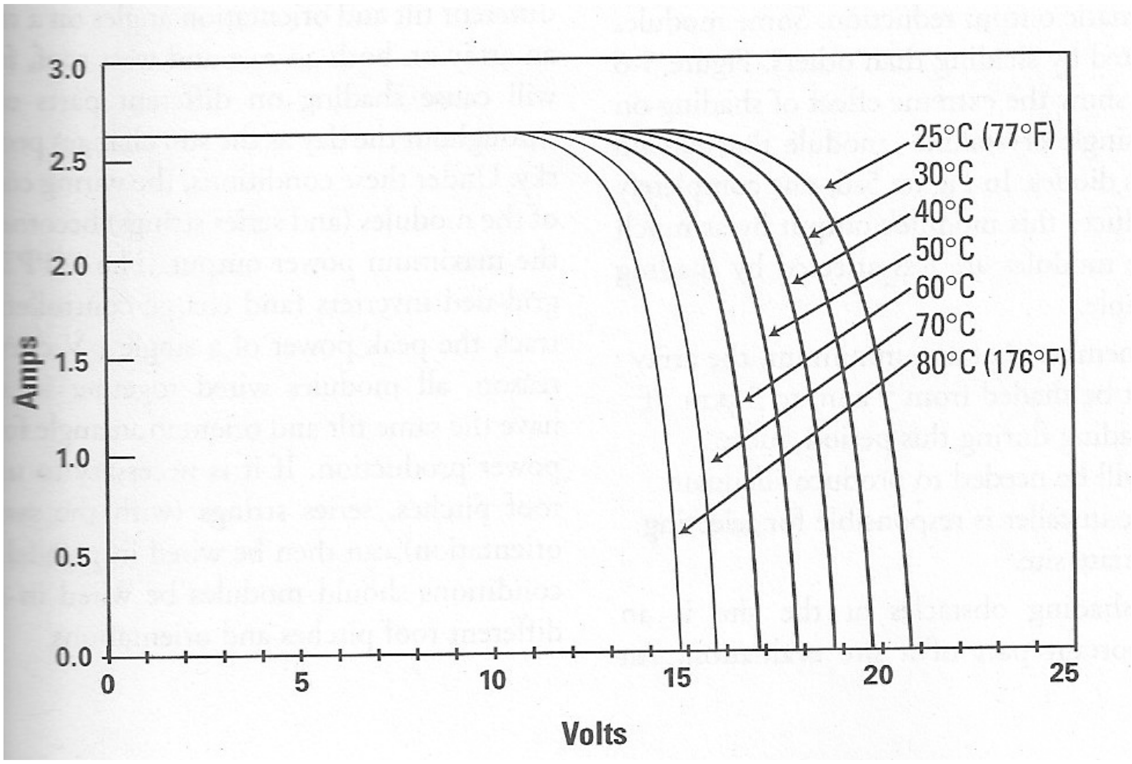


Figure 42. The effect of temperature on photovoltaic modules
(Solar Energy International, 2007, p. 55)

Water in the form of precipitation is one of the potentially most harmful elements that can impact the functioning of the photovoltaic cell. However, modules are carefully designed to resist the penetration of water beyond the protective exterior.

Internal elements

The internal elements within the PV module system generally consist of the electricity-generating PV cells, protective glazing, supportive aluminum frame, and the inter-module wiring that allows modules to be connected in order to produce sufficient electricity as a larger array. Individually, photovoltaic cells can provide very small voltages, typically between 0.55 and 0.72 V. For most practical uses, solar cells are wired together in parallel to increase the available voltage, and can be done in infinite numbers (Häberlin, 2013). Most common photovoltaic modules consist of 36 cells wired together to for 12 V systems (with a power output of 50 W) or 72 cells for a 24 V system (with a power output around 200 W), and enclosed in protective module casing (glass face and metal frame) (Häberlin, 2013). The *transparent cover* that protects solar cells is specially designed to withstand weather such as hail and extreme temperatures with tempered low-iron glass that is highly transparent (Häberlin, 2013). The *frame* that supports the cells within the module is typically made of aluminum (Häberlin, 2013).

In most cases, photovoltaic modules are wired with other identical modules to create a system, called an array, with enough voltage to satisfy the requirements of the *inverter* (Solar Energy International, 2007). This is the node connecting the modules to one another and to the larger building system to deliver usable energy.

6.3 Building with photovoltaic array

In distributed energy systems, the way in which energy is produced and consumed within the building connected to a single array represents a unique system. The system includes the electricity-producing technology as well as the electricity-consuming technology and the people who operate them. The purpose of this system, similar to the function of the plant system, is to sustain life through comfort and support the productivity of occupants to live, work, or play depending on the type of building.

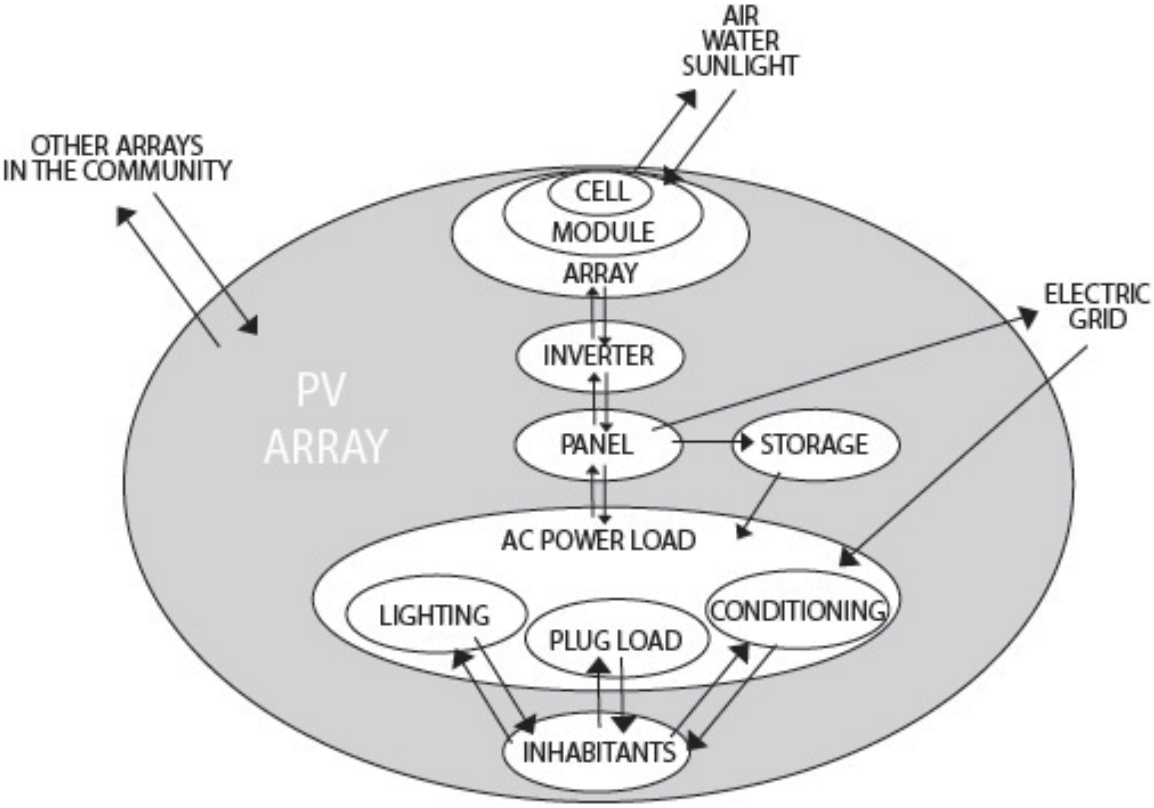


Figure 43. Photovoltaic array system
Developed by author

Environmental elements

Just as at the module scale, environmental elements such as solar radiation, air, and water all interact with the system. However, at the building array scale, these elements interact with the building itself to impact not only the supply, but also the human demand for electricity based on needs or perceived needs. The source of solar radiation, climate and air are the same as described above. However, when expanding out view to the entire photovoltaic array, other elements of the built environment begin to interact with the system. Neighboring buildings (those that also exist in the same community or neighborhood) likely play a role in the building type and the occupant demographics. The surrounding buildings can also play an important role in determining when and where on the site solar radiation may be obstructed. The natural landscape on site can also be a source of obstruction of solar radiation.

Internal elements

A photovoltaic array can consist of any number of modules seen fit to the demand of the building or resources of the investor and can be installed in a variety of configurations. Ideally, the number of modules in an array will depend on the energy demand of the building itself (which in turn depends on the building type and the occupants it serves). However, in many cases the number of modules depends on the available square footage or even more likely, the financial resources available to the building owners (Solar Energy International, 2007). There are widely recognized optimal installation patterns throughout the photovoltaic industry, however, the ultimate orientation of the installed panel is generally decided based on feasibility (Solar Energy International, 2007). The total capacity of the array is a direct function of the size of the array, the orientation of the panels, the inherent efficiencies of the panels, and the availability of sunlight (determined by environmental conditions including elements of the built environment). Current conventional PV modules are designed to allow for scalability.

The array produces direct current electricity through the processes explained in the previous chapters and is delivered to the larger building system as usable electricity after passing through an *inverter*, which transforms direct current electricity to the alternating current electricity that most appliances and electronics require. The electricity that is used throughout the building is managed via the *main distribution panel*. In a grid-tied building with a PV array, electricity demand can be satisfied from three distinct sources: from the PV through the inverter, from a storage system if one exists, or from the grid directly. As discussed in the literature review, the majority of buildings with distributed energy production such as PV arrays are also connected to the grid as back-up power, supplemental power, or as an alternative to installing a storage system. There are several potential technologies that could be used to store the electricity produced by PVs during peak solar radiation hours to be used at peak energy consumption hours. Currently it is most common to see the grid used as a 'storage' unit. However, there are some distributed energy producers that utilize batteries.

As mentioned, the building energy demand can be used to determine the optimum size for the photovoltaic array. However, in many dense urban areas, the energy demand of buildings are greater than the energy that can be produced in the available square footage for installing a PV array. Therefore, the potential energy that can be produced within the space available could become a measure for success for sustainable energy use. Generally, the building energy consumption is a function of the building's purpose, size, and construction type. However, perhaps most important to the energy demand are the people inhabiting the building. The building type will likely determine the types of people who inhabit the building and both the building type and the humans inhabiting the building are likely to determine the building energy consumption. Their purpose for inhabiting the building determines the action that occurs within. Today, most all actions require building operations that require the consumption of some form of energy.

Aside from the climatic conditions detailed in the environmental elements portion of this section, there are also biological elements of the surrounding ecosystem that influence both the ability of the array to produce energy and the building's patterns of consumption. Patterns of shade and sun can have a great influence on the productivity of the array. Shading from ecosystem elements can also help or hinder the efficiency of energy consumption within the building.

The technological system in which energy production from photovoltaics and energy consumption occurs within a building are complex, however, it is but a subsystem of the larger energy community of the neighborhood, municipality, or even region. In the following section we will take a step back to look at the larger energy production-consumption system to examine the interactions, or lack thereof, in communities of buildings.

6.4 Community of buildings with photovoltaic arrays

The boundaries of the photovoltaic energy system at the community or neighborhood scale are similar to those of the ecosystem in that they are difficult to define. Boundaries may be natural (a river, coastline, elevation change, etc.) or artificial (a major street, a change in zoning or land use, a change in culture, etc.). The community-level system includes all elements within the designated boundaries as well as any external elements directly interacting with or entering the system. The purpose of this system, conventionally, is to sustain the productivity of all the artificial elements of system (often at the demise of the natural elements).

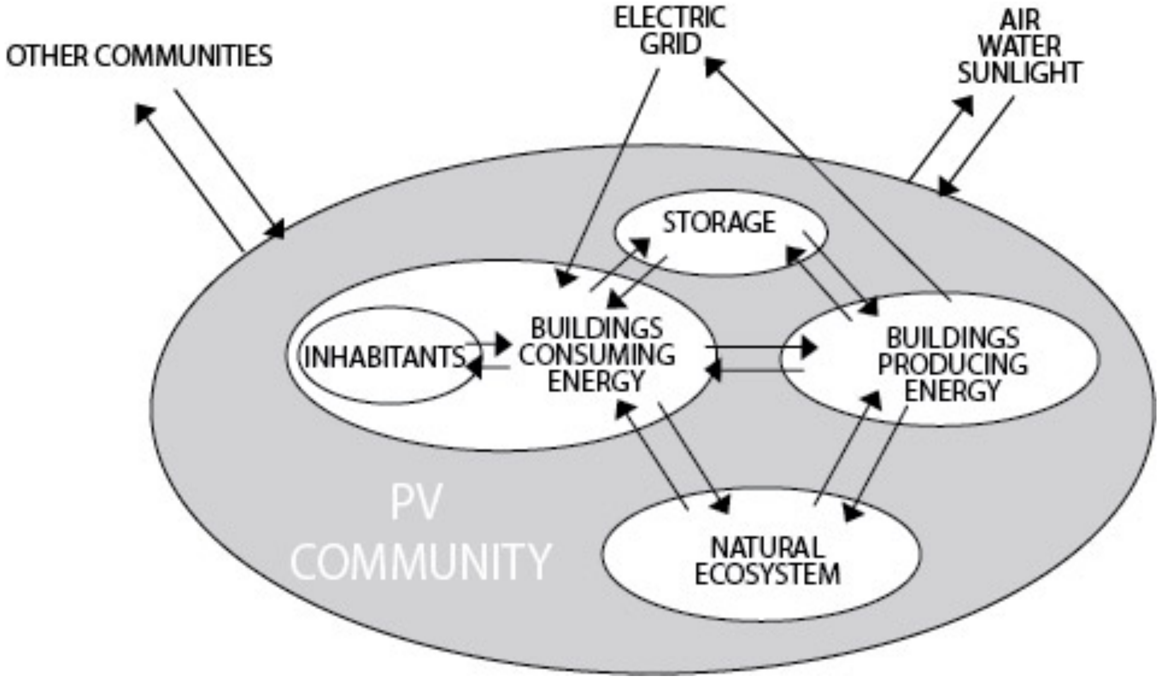


Figure 44. Community of photovoltaic arrays system map
Developed by author

Environmental elements

As at other scales, the environmental elements include solar radiation, climatic conditions, and the flow of water, air, energy and information. However, distinct from other scales, the environmental elements in a PV community also include other neighboring communities and the larger electric grid.

Internal elements

In a community or neighborhood supported by distributed energy production, the two major internal elements would consist of *buildings producing energy* and *buildings consuming energy*. Each building's ability to produce energy is characterized by its height, its orientation, and its relative position to other elements within the community.

Each *building consuming energy* is characterized by its age, construction, orientation, size, and purpose among other possible variables. Physical characteristics of buildings and the attached photovoltaic arrays affect energy loads related to responses to environmental conditions and to each other, however it is the inhabitants, the people, who determine what an appropriate response to these environmental conditions might consist of. Though it is not the focus of this study, perhaps the most critical internal elements of the socio-technological system of photovoltaic energy production and consumption are the humans inhabiting the community and their energy demanding behaviors. Their demand for energy is likely a function of both their purpose for inhabiting the community and the culture to which they belong. They could be residents of the community, employed within the community, students within the community, or simply recreational visitors to the community. The inhabitants could be wealthy or not, educated to any varying degree, aware or unaware of energy efficiency measures, young or old, etc. All of these scenarios would likely yield a different schedule and intensity of energy demand on the community. The influence of human purposes and cultures on energy use is illustrated in Table 09 using energy usage intensity measured in kBTU per square foot for several building use types.

The way energy enters, exits, and moves through the community would be greatly affected by the presence of *energy-producing buildings*. Energy-producing buildings would not only have environmental and energy implications for the condition of the community, but also educational and cultural implications. The tangibility of photovoltaic arrays and the visibility of energy systems within the community could lead to shifts in perceptions of human-energy relationships consequently leading to cultural and behavioral shifts.

Non-human, non-built elements throughout the system, or '*natural' elements*, also affect the way in which energy flows though the system. Natural elements can inhibit energy production by interfering with photovoltaic exposure to solar radiation, reduce energy demand by intercepting solar radiation from conditioned built spaces in warm months, and contribute to either desirable or undesirable microclimates within the community.

		Source EUI (kBTU/ft2)	Site EUI (kBTU/ft2)
Residential	Single-family	NA	NA
	Multi-family	NA	NA
	Senior care	243.2	125.7
Commercial	Office	148.1	67.3
	Banking branch	252.8	87.0
	Medical office	116.7	44.4
	Retail	114.4	47.1
	Convenience store	536.3	192.9
	Grocery	480.0	185.5
	Restaurant/bar	432.0	223.8
	Fast food	1015.3	384.0
Public	Hospital	389.8	196.9
	Library	235.6	91.6
	Police Station	154.4	88.3
	Gathering	69.8	45.3
	Post Office	100.4	49.6
	Transit terminal	85.1	45.3
Educational	K-12 school	141.4	58.2
	University	262.6	130.7
	Vocational School	141.4	59.6
	Daycare	145.7	70.9
Cultural	Recreation	96.8	41.2
	Worship facility	70.7	36.8
Mixed use		123.1	78.8

Table 09. Energy Usage Intensity by building type
Based on content from (ENERGY STAR, 2013)

The human-driven energy demand throughout the community is manifested in specific energy-consuming technologies. Lighting loads, plug loads (appliances), and conditioning loads are the three types of energy demands in these buildings. The schedule on which each peaks and lessens can be influenced by a myriad of factors, which may or may not be fixed: environmental conditions, time of day, human schedules, etc.

7 Applying the Biomimetic Lens

In this chapter, the newly constructed biomimetic lens will be applied to each scale and period of time outlined in the system analysis preceding this section. For each scale, the biomimetic lens will allow us to compare the current state of conventional photovoltaic system to its counterpart in photosynthesis. Statements of similarity or suggestions for correcting differences will be made drawing from alternative emerging photovoltaic technologies discussed in the literature review or novel concepts inspired by the investigation into the photosynthetic process. Suggestions will include an explanation of the source of inspiration (the processes that will be mimicked), suggested design methods for incorporating biomimetic inspiration, and the way in which the success of the biomimetic strategy could be measured.

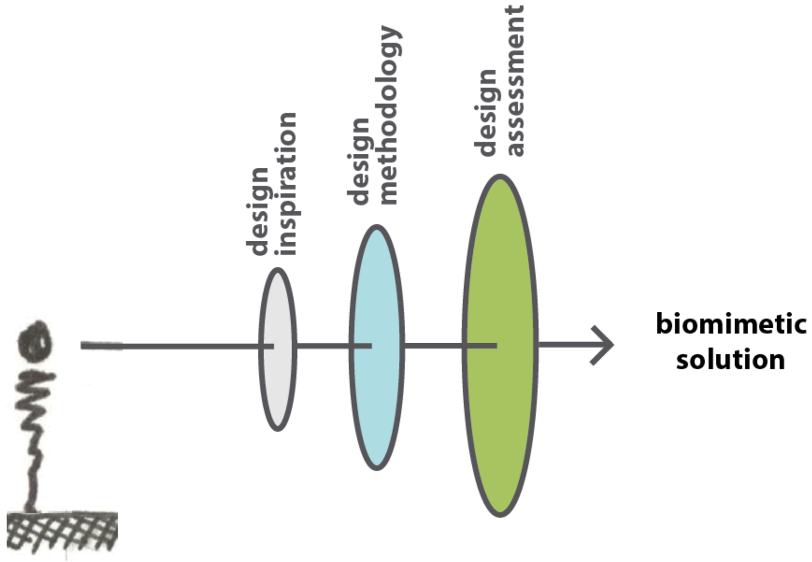


Figure 45. Applying the biomimetic lens
Developed by author

In addition to the nesting of systems across scales and across time, the success of biological systems is due to the fact that they are embedded in local environmental conditions, which serve as both conditions for thriving and constraint. Since a potential biomimetic solar energy production and consumption system is a sociotechnical system the consideration of local social and economic conditions and constrains is also critical. These ecological, social, and economic systems are not independent, but influence one another. The solutions that emerge from this exercise are not meant to equate to the ultimate solution for a sustainable energy system as achieved through biomimetic thinking, but instead a proposal for further research conducted by an interdisciplinary team.

7.1 Solar cell / Photosynthetic cell scale

There are several characteristics of the biological system supporting photosynthetic activity at the cellular scale that can be applied to the design of a biomimetic solar energy cell. These involve principles related to material composition and electrochemical processes for creating and capturing energy.

	SOURCE OF INSPIRATION	DESIGN METHODS	MEASURE OF SUCCESS
SYSTEM ORGANIZATION	*At this scale components are purposefully integrated and designed for cooperation; further study required to make recommendations*		
EXISTS WITHIN LOCAL CONDITIONS	Runs on solar energy	*Already operates on locally available energy*	
	Made of local materials	Design to utilize materials that are available or could be transported with reason	Cells are constructed using 'local' materials or those that can be transported using renewable energy
RESILIENT THROUGH DIVERSITY	Arrangement of chloroplasts	Design with dyes to capture sunlight	*Further study required to make a recommendation*
WASTE IS REPURPOSED	*At this scale resulting materials and energy are repurposed; further study required to make recommendations*		

Table 10. Summary of biomimetic solutions at the photovoltaic cell / photosynthetic cell scale
Developed by author

System-based organization

The structure of both photosynthetic cells and photovoltaic cells are organized in an intentional pattern, however the system of organization varies between the biological and technical systems. When looking at the molecular organization of photovoltaic cells as they compare to photosynthetic cell, there is opportunity for the less uniform nature of photosynthetic cells to inspire the design of a biomimetic photovoltaic cell.

Functionally, elements in both systems are purposefully integrated and designed for cooperation. There are, however, several system-based organizational lessons that can be learned from the photosynthetic process and applied to the envisioned biomimetic solar energy system. The distribution of photosynthetic cells within the larger system of plant cells is different than the distribution of photovoltaic cells within the solar panel. As discussed in the photovoltaic module chapter, the connections between photovoltaic cells need to be wired in series in order to achieve a useful power output. However, the current conventional wiring system allows interruptions affecting one cell to be detrimental to the overall efficiency of the system. If the system of cells was organized in a way that detected and self-corrected interruptions in solar energy, this loss of efficiency could be avoided. This is similar to the way smart grid technology on a larger scale accounts for interruptions in energy distribution and reroutes energy to ensure sustained functioning. Further research in emerging smart grid technologies and the scalability of the lessons they provide should be conducted before designing a new energy delivery system. Approaching this research in a similar manner to the analogy research conducted in this study is recommended.

In a biomimetic solar energy cell, success would be measured by the quality of interconnection it has to neighboring cells. This could be measured in terms of probability or risk of operational interruption.

Exists within local conditions

Existing within local conditions refers to both the energy that is needed to sustain the system and the materials that make up the system. The ability to operate within local conditions is inherent to the design of photovoltaic cells, but their ability to also be made from locally available materials could provide further inspiration. Biological systems can achieve equivalent or proportionally higher performance than those of many technical systems using fewer material and energy resources entirely within local conditions. A technological system that mimics this characteristic of biological systems would require the use of immediately available materials.

Functionally, both the photovoltaic cell and the photosynthetic cell are powered by locally available energy in the form of solar radiation. However, chloroplasts have the flexibility to adapt to take full advantage of the local conditions, whereas conventional photovoltaics are static. Once manufactured, transported, and installed, conventional photovoltaic cells already function using the energy that is available on site just as chloroplasts do. However, when looking at the building system as a whole, in most cases photovoltaics cannot use the naturally available energy from the sun to produce enough energy to support the demand on site. This will be addressed when discussing the plant / building scale.

The fact that current conventional photovoltaics must be manufactured offsite, transported, and then installed onsite indicates that materials do not exist within local conditions. Photosynthetic cells and the larger systems they belong to are constructed of immediately available local materials. Even emerging organic solar cell technology discussed in the review of photovoltaic literature has some promise as an eventual path to less toxic material, but still cannot be produced locally using local resources because of the energy intensity required in the production process. The manufacture of photovoltaics would also violate current political and regulatory conditions that are in place to protect the inhabitants of the community. Biomimicry, as a potential path to sustainability that embraces socio-technological solutions, would not necessarily call for a photovoltaic cell that could be made from naturally occurring materials onsite in order to successfully exist within local conditions. Locally available materials could be interpreted to include waste materials that are currently produced onsite as the result of social or economic activity already occurring.

A photovoltaic cell that successfully exists in local conditions could be measured by the ability for it to be constructed using materials that are onsite and ideally made from materials that no longer have use in their original form. In biological systems, often times new plants do not sprout directly adjacent to the plant from which the seed fell. Instead there are many ways in which a seed can be dispersed throughout an ecosystem or to a neighboring system including wind power, water, or being carried by a mobile species to another location. This could suggest that a photovoltaic that exists within local conditions does not necessarily have to be manufactured entirely onsite. There may be a reasonable amount of energy that can be used to transport a photovoltaic cell to the site on which it will exist for its functional life while still being held to the same standards as non-human ‘nature’. This reasonable amount of energy may be that it does not require more energy than is *proportional* to the energy typically used for seed dispersal which could include animal transport, wind power, etc.

For socio-technological systems, existing within local conditions refers to not only environmental conditions, but also political and regulatory conditions. Though the operation of the photovoltaic cells do not currently interfere with political regulations, other phases of the lifecycle of photovoltaics such as manufacture relate to regulatory conditions like city codes related to manufacturing activities on the site in question.

Resilient through diversity

Inspiration can be drawn from the diversity of chlorophyll position and type and how this diversity leads to more productive photosynthesis. There are examples of emerging photovoltaic technologies, such as tandem photovoltaics, that may or may not have been developed as a result of inspiration, but suggest a similar trajectory of development.

Functionally, the organic, non-linear arrangement of the chloroplasts allows greater potential for incident light at many different angles and wavelengths to stimulate the photosynthetic process. In contrast, the uniform, linear arrangement of PV cells is designed to optimize efficiency, but the arrangement of cells with more diverse components and connections to take advantage of more diffuse and reflected light that it is currently not taken advantage of. Although conventional photovoltaic cells do not exhibit diversity of components nor connections, there are hybrid photovoltaics that do.

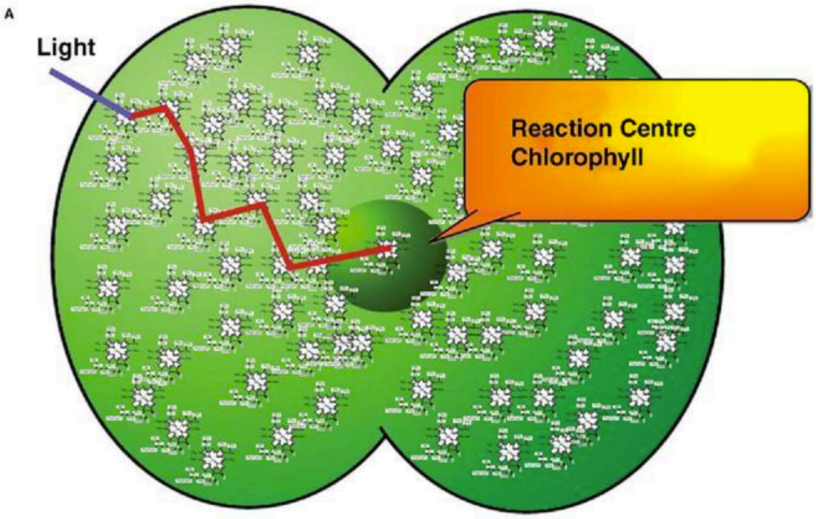


Figure 46. The capture of light by chlorophyll
The capture of light energy…Schematic representation of the antenna complex. Around 200 chlorophyll molecules are arranged on a protein complex, so that they can interact with light. The array of chlorophyll molecules is such that, if a suitable wavelength of light strikes any molecule, then an electron will move into an excited state in a higher energy level (Scott, 2008, p. 23).

In addition to a diverse set of connections, a diverse use of technologies responding to unique solar conditions may also improve the productivity of photovoltaics. Similar to the integration of multiple forms of chlorophyll in plant cells, the use of hybrid and tandem photovoltaic cell technologies can help increase the efficiency by increasing the range of wavelengths that will invoke a photovoltaic reaction. A successful biomimetic solar cell would consist of diverse components with diverse connections. Similar to the conditions of success outlined in the system organization section above, successfully diverse connections could be measured in terms of risk of interrupted operation. Diverse components could be measured by their combined efficiencies, the ranges of wavelengths they respond to, or the combination of unique band gaps across technologies used.

Waste is repurposed

In the actual operational period within the lifecycle of both the biological and technological system, 'waste', or the non-productive resultants of one process, is repurposed in a consequent process. In chloroplast systems, all the resultant waste energy from chemical reactions (ADP/NADP) are repurposed as electron carries in the next round of the photosynthetic reaction. In photovoltaics electrons are cycled through the semiconductors with, in most cases, little loss of efficiency. And, in both the biological and technological system waste energy is lost as waste heat. The potential for biomimetic thinking to improve the waste management at the scale of the photovoltaic cell is outside of the time period that is focus of this study (the operational life) and instead in the extraction, manufacturing, and end of life periods.

7.2 Module / leaf scale

Some of the principles of operation found in the photosynthetic process at the leaf scale can be applied to the solar module scale to promote more sustainable functioning. The biological principles relevant to the technological system largely involve those related to material structure and scalability of technology.

	SOURCE OF INSPIRATION	DESIGN METHODS	MEASURE OF SUCCESS
SYSTEM ORGANIZATION	Leaf position	Design for modules to cooperate	Modules adjust to maximize system productivity *not* only module productivity
EXISTS WITHIN LOCAL CONDITIONS	Heliotropism	Design modules to respond to environmental, economic, and social conditions	Modules respond automatically to solar radiation based on real-time economic conditions and human demand
RESILIENT THROUGH DIVERSITY	Leaf types	Design for responses to a variety of solar conditions	Modules not only respond to conditions in the short term, but also have the capability to evolve in future iterations
WASTE IS REPURPOSED	*Opportunities lie outside of the operational period of the photovoltaic lifecycle*		

Table 11. Summary of biomimetic solutions at the module / leaf scale
Developed by author

Systems-based organization

There are several examples of photovoltaic module organization that are inspired by the way in which leaves are organized. One product inspired by the organization of leaves is the Solar Ivy developed by Brooklyn firm Sustainably Minded Interactive Technology seen in Figure 47 (Biomimicry 3.8). This product utilizes alternating orientations similar to those of leaves in a single plant. It also takes advantage of a typically overlook application for solar energy – vertical surfaces. The manner in which the inspiration has been manifested in the artifact itself may or may not have a positive impact on the function of the photovoltaic modules in this and other examples of leaf-inspired module systems.

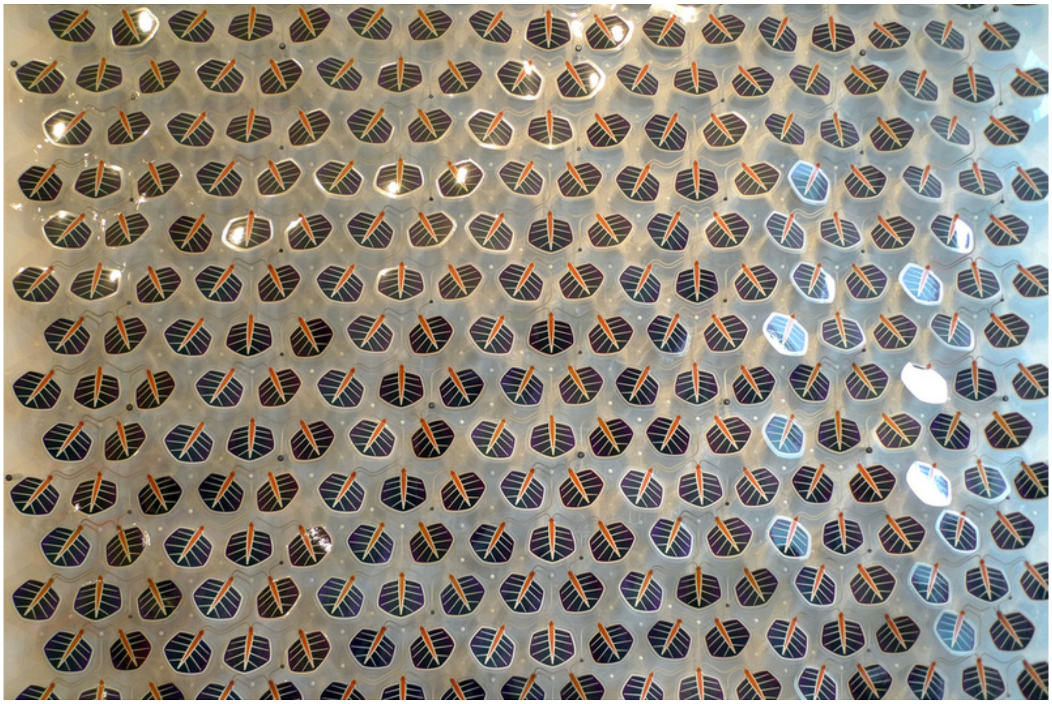


Figure 47. Photovoltaic modules inspired by leaves
(Biomimicry 3.8)

Though there are a wide variety of patterns of leaf positions, most leaves are arranged in a way that optimizes some condition (solar gain, water retention, etc). Conventional distributed generation photovoltaic modules are typically installed a uniformly based on a formula that is meant to optimize efficiency to the extent that it can be optimized in a fixed position. This uniformity is not limited to the modules' orientation, but also applies to the way the system is wired. Similar to the series connections that are necessary between solar cells, many times connections between a number of solar modules also have to be in series in order to reach useful voltage as discussed in the previous chapter. This makes arrays at risk for larger interruptions when there are issues with one module.

A successfully systematically organized biomimetic solar module would mimic the physical positioning of leaves as well as the systematic connection of leaves to the larger system. A successfully biomimetic system would also include modules that not only respond to environmental conditions, but also respond to their neighboring modules to prioritize the productivity of the system over the productivity of any one module.

Exists within local conditions

Leaves respond to a wide variety of changing environmental conditions to protect or optimize themselves and the plant of which they are a part. There are many opportunities for the designers of biomimetic solar modules to draw inspiration to the integration of leaves and their local conditions to design modules that respond to not only environmental conditions, but economic and social conditions as well.

There are many species of plants that maximize their photosynthetic productivity by tracking the sun via heliotropism. There is great potential for solar modules to do the same. There are already several examples of photovoltaic modules that move with the sun to optimize their ability to produce energy throughout the day, however, commercial applications track the sun based on programmable schedules, typically not as a response to an environmental stimulus. There are applications in other material science and engineering contexts in which technologies do respond directly to environmental stimuli. Further research including an analogy analysis of such applications against the potential for environmentally sensitive solar modules may result in a biomimetic solution.

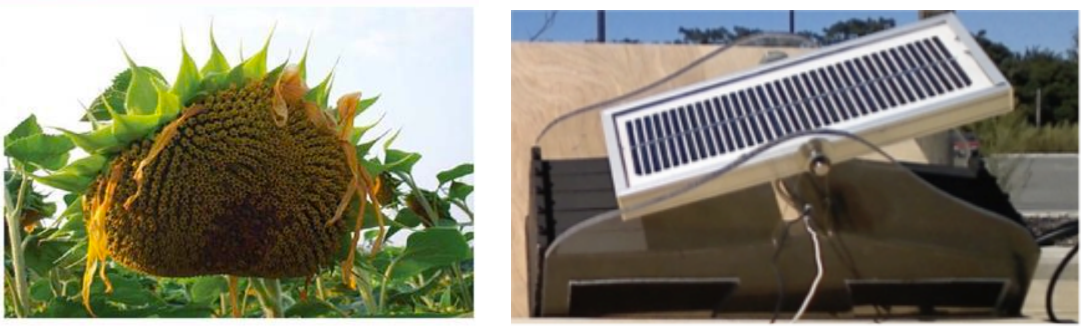


Figure 48. Heliotropism in biological and technological systems
Left: (Scott, 2008, p. 166)
Right: (Biomimicry 3.8)

Unlike approaches to analyzing biological systems in the tradition of the hard sciences, socio-technological systems require attention to the social and economic context in addition to non-human environmental conditions. With increasing ability to access immediate, *real-*

time information about trends in energy production and consumption there is potential to incorporate that information into distributed generation as well. In biological systems information is exchanged between elements to monitor the production and distribution of energy throughout the system. In the socio-technological system of solar energy production, capital, in addition to electricity, becomes an outcome of the processes. Progressive utility programs are offering real-time pricing for electricity. At various points throughout the day, the cost to produce and deliver one kilowatt of energy varies based on the current demand. Energy consumers that opt into a real-time pricing program are rewarded for reducing peak energy demand by paying the hourly wholesale market price (Commonwealth Edison Company, 2013). Using a local real-time pricing program like the one offered by Chicago's utility provider, Commonwealth Edison Company, in conjunction with smart appliances, information could be exchanged between energy producing and energy consuming technologies within the system to maximize profits. Shutting down high energy consuming technologies when the price is high and selling that saved energy back to the grid will allow higher profit, which can in turn be invested into growing your energy producing potential.

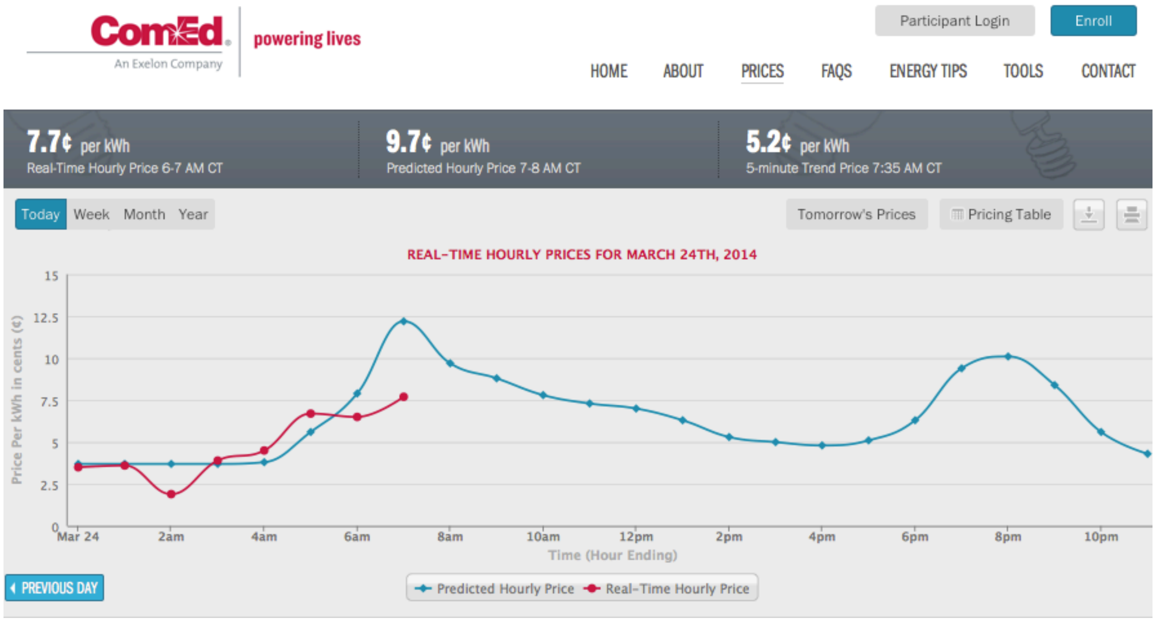


Figure 49. Real-time pricing of electricity
(Commonwealth Edison Company, 2013)

As seen throughout the analysis of this study, a major barrier to the success of photovoltaics as a sustainable energy source is its inability to produce enough energy to meet the demand of the site. This will need to be addressed in further research: studying how the plant system allocates the energy produced by autotrophic organs to sustain life and how these principles may or may not apply to the allocation of energy in the built environment. Successfully designing a biomimetic solar energy module that exists within local conditions would involve a system that responds to local environmental and economic conditions to mimic plant responses to environmental conditions that determine the allocation of energy throughout the plant.

Resilient through diversity

The same design principles that could potentially drive more a more system-based organization could also support resilient functioning through diversity. Diverse photovoltaic cells within a module (as discussed in the cell-scale section above) is one way to use diverse components to improve resiliency, but another approach at the module level would be to have modules of varying materials, orientation, and responsiveness to specific wavelengths of light (with specific band gaps). This could support resiliency though diversity at the building scale as well if the orientation or material type was matched and wired to specific energy-consuming technologies within the building. This will be discussed at more length in the following section on building-scale biomimetic strategies.

Resiliency can also be encouraged by the module's ability to adapt to changing conditions in the short term, as discussed in the previous section on responding to local conditions, as well as flexibility to evolve with future iterations. Designing modules that can be integrated with other types of modules or other types of clean energy production technologies would improve the resiliency of the system as a whole.

Waste is repurposed

As in the case of the cell-scale, 'waste' is repurposed throughout the operational life of the photovoltaic module. The opportunities for improving the sustainability of this technology are in the extraction, manufacturing, and en-of-life management stages of the photovoltaic lifecycle, which are not the focus of this study. There is more opportunity during the operational life the next scale up: the building array as it mimics the plant.

7.3 Building array / plant scale

The lessons learned at the plant scale can be applied to the building scale. These lessons involve the themes of energy supply and demand constraints – the maximum energy supply given local conditions, as well as appropriate methods for allocating energy to components performing various necessary functions toward whole-system function.

	SOURCE OF INSPIRATION	DESIGN METHODS	MEASURE OF SUCCESS
SYSTEM ORGANIZATION	Cooperation of autotrophic and heterotrophic organs	Design for information exchange with smart appliances	Energy produced by the array is allocated to
	Allocation of carbon to promote growth	Design to grow the solar energy array incrementally	Energy produced is allocated first sustain the production of arrays; cost savings are allocated to grow the array until all building function can be supported
EXISTS WITHIN LOCAL CONDITIONS	Evolving rather than tackling unsolvable problems	Design for energy efficiency and storage based on stress responses	Energy is used only when necessary and energy is stored locally
RESILIENT THROUGH DIVERSITY	Diurnal and annual cycles of consumption	Design to instill diversity in consumption patterns when possible	Energy demand is controlled to reflect supply capabilities (which might include storage technologies)
WASTE IS REPURPOSED	Entropy	Design for waste heat to be repurposed	Energy is not left unharnessed

Table 12. Summary of biomimetic solutions at the building array / plant scale
Developed by author

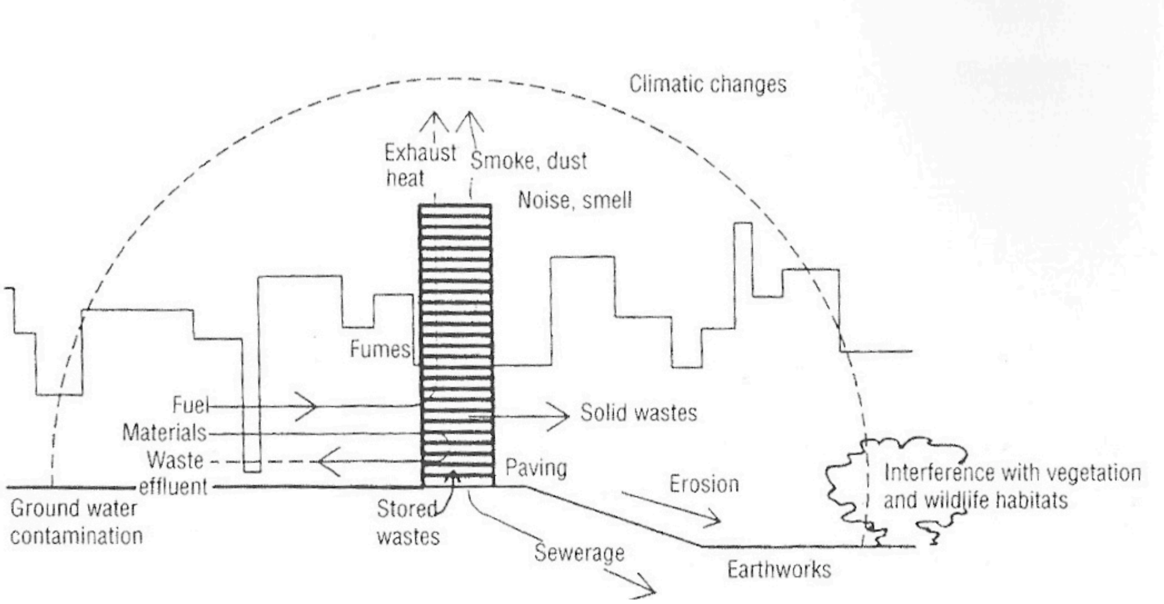


Figure 50. Impacts of the built environment on its surroundings
(Gruber, 2011, p. 82)

System-based organization

In plants, autotrophic and heterotrophic organs are purposefully integrated and are designed to cooperate to support the overall function of the plant system. According to Smith and Smith:

> Different plant tissues are involved in the acquisition of essential resources necessary to support photosynthesis and growth. Leaf tissue is the photosynthetic surface, providing access to the essential resources of solar radiation and CO_2. Stem tissue provides vertical support, elevating leaves above the substrate and increasing access to solar radiation in dense stands of plants. It also provides the conductive tissue necessary to mobilize water and nutrients to the leaves. The root tissue provides access to below the group resources such as water and nutrients in the underlying substrate" (Smith & Smith, 2008, p. 90).

A biomimetic solar energy system in the built environment would also integrate components and design for cooperation rather than designing for the solar array to provide energy without receiving anything back from the rest of the building.

A biomimetic solar energy array that works similar to conventional photovoltaic arrays – one that does not require inputs apart from solar radiation to produce energy – could still benefit from the support of 'heterotrophic' building components. Support could come in the form of information rather than elemental nutrients and water. In alignment with emerging smart grid and smart appliance technology, ‘heterotrophic’ components within the building such as appliances and electronics could communicate with the biomimetic solar array to allocate energy appropriately to tasks throughout the day. These technologies already exist to some extent, and further research should be conducted in the areas of smart homes and smart grids before a concrete strategy can be developed.

In plants, “the allocation of carbon to the further production of leaf tissue will promote the fastest growth. Increased allocation to leaf tissue increases the photosynthetic surface, which increases the rate of carbon uptake as well as carbon loss due to respiration” (Smith & Smith, 2008, p. 90). This system for the allocating resources has many implications for a building (and community) scale biomimetic solar energy system. However, since social and economic factors are a part of the socio-technological solar energy system, resources are not limited to the energy produced, but also capital gained. There are a couple different ways that this notion of allocating resource first to increase energy-producing surface area to ‘grow the solar energy market’ in the built environment.

If the most effective way to produce solar modules is still mass-producing them in an industrial facility, then the resources of the facility should first go toward growing their own array to support the operations of their facilities before they are allocated elsewhere. This may mean installing a small ‘seedling’ array to initiate the process, and using the energy produced from this initial array to produce more until the array is large enough to support the operations of the facility. The facility can then begin dispersing biomimetic solar energy modules to other locations to begin their own *seed germination* and growing process. Means of distribution that might qualify as biomimetic will be discussed in the next section defining local conditions. If the solar energy modules cannot be produced onsite, residential and commercial buildings can still model their resource allocation after plant systems upon receiving a seed array from a local manufacturer. In residential buildings, a biomimetic solar energy array will save residents money that would otherwise be allocated to purchasing conventionally produced, grid-delivered energy. In commercial buildings the energy produced will not only save money, but also contributes to capital accumulation that is made possible through the use of the energy consumed for commercial purposes. A biomimetic approach to maximizing productivity, might assert that a portion of capital gained as a result of the energy produced should be allocated to growing the array until the array can support the building’s operations in full. For buildings with commercial spaces, a significant percentage of money made via the energy produced by solar array should be allocated to "growing" the solar array. Unlike photosynthesis, given solar energy systems are embedded in the social and economic context of the site, one of the outputs associated with solar arrays are the goods is being produced with the electricity provided. This may be in the form of services or products. This accumulation of earnings can be stored like carbon in the plant to help the array, and therefore the business itself, grow in the future.

Exists within the limits of local conditions

As suggested above, the systematic allocation of energy throughout the plant could become a model for allocating energy throughout a building system. However, the total energy available to be distributed is dependent on locally available solar radiation. Measures promoting energy efficient consumption should be taken in concert with renewable energy production. As expressed by Michael Pawlyn:

> Humans tend to tackle problems head-on whereas living organisms, through the process of evolution have tended to change a problem before resolving it. Nowhere is this more apparent than in the realm of energy. We have generally tried to meet our perceived needs by simply creating more and more energy rather than thinking about how we could develop solutions that, just as in nature, need far less energy in the first place (Pawlyn, 2011, p. 91).

In addition, the efficiency Pawlyn talks about should not only come from the efficient use of energy within the building system, but also in the production and transport of all material goods within the building system.

Another problem that has been associated with conventional photovoltaic arrays attempting to achieve sustainability is the high electricity demand in the evenings and throughout the night. This is especially difficult for buildings demanding conditioning in the winter in local Midwest environmental conditions. Further research in energy efficiency may offer potential solutions. Additionally, once plants have matured, a substantial amount of energy that is produced is allocated toward growing and readying seeds for distribution to ensure the continuation of the species. It is unlikely that biomimetic solar energy arrays will be literally grown on site (like asexual plant reproduction), but the energy used in the distribution methods could mimic that used in the distribution of seeds in nature. In the non-human world plant seeds are often dispersed via wind, water, or animals that unintentionally carry the seeds using the energy they gain from consuming plants. Solar arrays that are produced elsewhere, but make it to the site via transportation, say a truck, that was powered by wind, water, or the same clean and renewable energy source that was used to produce the ‘seed’ itself could meet the measures of success of biomimicry.

Resiliency through diversity

In plants, heterotrophic organs use energy in diverse ways and demand energy at different points of the daily and seasonal cycles. To expand on the ideas related to systems-based organization, in a biomimetic solar energy powered building the interconnection between energy production and energy consumption would be made explicit through the use of both smart technologies and educated humans, that have the ability to prioritize energy-consuming activities based on available energy. Diversity in both the energy consuming technologies within the building and the diversity of the culture of the humans demanding their use of energy would allow flexibility of demand resulting in a more resilient energy production-energy consumption relationship.

Waste is repurposed

Before getting to this scale, there was little room for improvement in terms of photovoltaics repurposing incremental system outputs. At the building level, however, there are two resultants from the photovoltaic process that can be utilized, but often go unharnessed. As discussed in the literature, there are hybrid solar energy systems that take advantage of waste heat. Typical increases in temperature do not increase the productivity of photovoltaics, but resultant heat could be utilized in a solar thermal system. This transforms a liability (excess heat) into an asset (excess energy) while also adding to the diversity of energy sources. The other type of ‘waste’ that may occur at the building scale is excess energy produced in non-grid-tied systems without storage. Though not common, connecting and feeding other buildings within the community could repurpose this ‘waste’ energy.

7.4 Community / ecosystem scale

The lessons learned at the ecosystem scale can be applied at the community or neighborhood scale. These lessons are around the themes of cooperation and competition among like-organisms as well as those that rely on the energy produced by autotrophic species populations.

	SOURCE OF INSPIRATION	DESIGN METHODS	MEASURE OF SUCCESS
SYSTEM ORGANIZATION	Vertical and horizontal structure organization	Design for varied strategies at different heights and different density across space	Energy production is optimized for the position of the energy producing technology
EXISTS WITHIN LOCAL CONDITIONS	Utilizing all local environmental conditions	Design for renewable energy production based on resource availability	Energy is produced exclusively within the community
RESILIENT THROUGH DIVERSITY	Species diversity	Design for a variety of energy consumers (quantity of energy needed, time demand, etc.)	Energy consumption at maximum matches energy production potential
WASTE IS REPURPOSED	Redirected energy	Design for integrated distributed generation (mini-grid)	Energy is immediately consumed locally; alternatively storage is made available

Table 13. Summary of biomimetic solutions at the community / ecosystem scale
Developed by author

System-based organization

The structure of the ecosystem and the way in which energy is circulated throughout the elements that structure has implications for the structure of distributed generation in a community. The vertical and horizontal structure of ecosystems as discussed in the section on the mechanics of photosynthesis suggests a systematic organization in order to fulfill a need for diversity. The structure of the ecosystem is successful when it allows for the efficient and effective exchange of materials, energy, and information between elements. Intentional flexibility of energy production and consumption would be an indicator of success in a biomimetic system-based organization.

Exists within the limits of local conditions

At the community-scale, there is more opportunity to leverage diverse energy sources to successfully run all activity entirely on locally available solar energy as ecosystems do. Optimizing the placement of solar energy systems as well as their integration with other renewable energy sources throughout the community allow a higher chance of successfully addressing the consumption outweighing production capacity issue seen at the building scale. Diversity is key to achieving sustained urban life within the limits of local conditions. The same principles discussed in the previous section outlining locally available materials at the building-scale. The boundaries of the community-scale system offer a larger and more diverse pool from which to choose.

Resiliency through diversity

In natural ecosystems, species diversity and species richness are often indicators of the health of the ecosystem as a whole. The suggestions mentioned in relation to the diversity of culture in humans and their energy-consuming technologies apply at this larger scale from building to building throughout a community. However, a resilient system would also have diverse connections in addition to diverse components. A community-scale smart grid system to assist with the allocation of energy to consumers based on a function of priority and equity may approach a community-scale biomimetic solution to energy distribution. Further research on smart grid technologies would be required. However, more importantly an in depth study of the sociopolitical system would be required to determine an appropriate function for allocating energy based on priority and equity.

Waste is repurposed

As mentioned throughout this chapter, photovoltaics are already largely successful at repurposing all 'waste' throughout the operational stage of the lifecycle. In current conventional photovoltaic systems, which assume distributed generation with grid connection; all waste energy is accounted for. However, energy lost as waste heat during transmission could be minimized by utilizing smart grid technology to enable neighboring energy-consuming buildings to exchange energy directly rather than sending any excess energy back into the larger grid system.

There have been many ideas discussed in this section – some more fully formed than others, some based on optimizing or repurposing current available technologies, and others suggesting the development of new technologies altogether. However, there is a handful of ideas that compliment each other and have the potential to become a system-based biomimetic solution to solar energy production. At the cell-scale, the use of tandem photovoltaics and hybrid methods as a means of creating diverse components and diverse connections to promote resiliency of the system seem feasible with current technology and effective at improving conventional photovoltaic systems as they currently exist. At the module-scale, tracking the sun to optimize performance and response to real-time pricing trends to maximize profits in grid-tied system demonstrates how responsiveness to local conditions can create additional capital to be used to further grow your photovoltaic system at the array-scale. At the building scale, developing a system for growing your PV array and better integrating renewable energy production and energy efficient consumption. At the community scale developing dynamic and diverse connections between producers and consumers could yield a more resilient and ultimately sustainable system. The next chapter offers a starting point for further interdisciplinary research addressing some of these ideas.

8 CONCLUSION

This chapter will address the effectiveness of the process used for applying biomimetic thinking to the design of a solar energy system, and propose further interdisciplinary research to strengthen the case for biomimetic solar energy as a sustainable solution.

8.1 Process prototype for biomimetic application

Less prescriptive than Julian Vincent's BioTRIZ and more systematic than shallow biomimicry's mere application of inspiration, this exercise of Nachtigall's approach to analogy research as described by Petra Gruber is a helpful tool for identifying potential biomimetic solutions. One aim of this study was to assign equal weight to both directionalities of biomimetic thinking: investigation and application. As mentioned in the literature review, throughout the biomimicry literature a pattern appeared. There are two categories that the majority of biomimetics fall into: natural scientists advocating for the use of a particularly remarkable natural process or system found in non-human 'nature' (investigation) and designers seeking solutions to a particularly difficult problem in the built world (application). Nachtigall's framework for analogy research was successful in allowing this study to look at biomimicry in a symmetrical way.

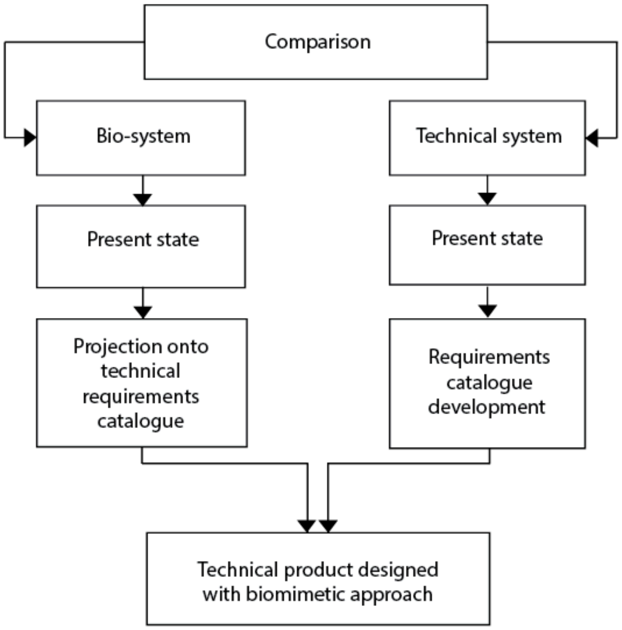


Figure 51. Analogy research
Based on content from (Gruber, 2011)

The next steps, beyond the scope of this study, for biomimetic solar energy should be applying this analogy research model to other relevant topics such as the ones listed in the following section.

8.2 Recommendations for further research

In the spirit of biomimicry, researching and building on existing initiatives and knowledge bases will be critical to growing the concept of biomimetic solar energy. Nature does not start from scratch – for millions of years nature has succeeded with research and development building on existing systems with small incremental changes. This chapter outlines existing areas of research that have the potential for becoming a foundation from which biomimetic solar energy research and implementation could grow.

Topic 1: Photovoltaic processes that mimic photosynthesis

Among the many emerging photovoltaic cell technologies, there is potential to take a biomimetic approach to further research and development. This research would be conducted at the photovoltaic cell scale and should be conducted as a collaboration between biologists, material scientists, and electrical engineers. Some key questions and anticipated findings are listed in the table below.

<table>
<tr><td>Topic</td><td colspan="2">Photovoltaic process that mimics photosynthesis</td></tr>
<tr><td rowspan="3">Research team</td><td colspan="2">Biologist</td></tr>
<tr><td colspan="2">Material scientist</td></tr>
<tr><td colspan="2">Electrical engineer</td></tr>
<tr><td rowspan="3">Key questions</td><td colspan="2">How does photosynthesis create energy from light?</td></tr>
<tr><td rowspan="2">What are the current photovoltaic technology trajectories?</td><td>What shortcoming(s) of conventional PV systems would a biomimetic technology attempt(s) to solve?</td></tr>
<tr><td>What PV technologies have been developed to address these problems to date?</td></tr>
<tr><td>Anticipated findings</td><td colspan="2">A new, economical and scalable solar energy cell built off current emerging technologies that prioritizes biomimetic goals to be determined by the research team</td></tr>
</table>

Table 14. Outline for Recommended Research Topic 1
Developed by author

Topic 2: Mimicking seed dispersal strategies for the transportation of photovoltaics

As mentioned in the previous chapter, it is likely that the mass-production of a biomimetic solar energy system will be preferable to onsite manufacturing, however, there is potential to find a way to transport solar technologies to the site using principles of biomimicry. This research would be conducted by biologists, ecologists, lifecycle analysts, and potentially transportation planners. The key questions and anticipated findings can be found below. The findings from this study may have larger implications for assessing the success of transportation activities in other lifecycle analyses.

Topic	Mimicking seed dispersal strategies for the transportation of photovoltaics	
Research team	Biologist/Ecologist	
	Transportation planner	
	Life cycle analyst	
Key questions	How much energy is required to disperse seeds from plants?	How much energy does it take to transport a seed?
		How much energy does the plant the seed becomes end up producing in its lifetime?
		What is the ratio of transportation energy to energy produced throughout its lifetime?
		What is a reasonable energy investment in transportation?
	Lifecycle analyst	How much energy will a photovoltaic array produce in its lifetime?
		Given the ratio determined for seeds and plants what is the appropriate energy investment in transportation
	Transportation planner	What transportation options would run on solar, wind, or water generated energy?
		Is it reasonable?
Anticipated findings	A target transportation energy investment based on the ratio of energy produced to seed dispersal energy demands; a proposed method of transportation and guidelines for distance	

Table 15. Outline for Recommended Research Topic 2
Developed by author

Topic 3: Building energy consumption that mimics the energy distribution in plants

One potential path to improved efficiency of energy use is to improve, or in many cases for the first time initiate, information exchange between energy-consuming technologies. Smart appliances could systematize and automate the energy-saving behavior that is encouraged by the increasing availability information such as that in real-time pricing programs described in the previous chapter. However, the social-nature of technological systems determine that the success of these strategies cannot be purely automated, but will require a balance of technological solutions and human behavior change through education on how energy is both produced and consumed. Some key questions to guide this area of research and the anticipated findings are outline in Table 16.

Topic	Building energy consumption that mimics the distribution of energy in plants	
Research team	Biologist	
	Building scientist	
	Information technologist	
	Behavior scientist	
Key questions	How do plants allocate carbon?	How are areas of the plant prioritized?
		How is energy moved throughout the plant?
		How is supply and demand communicated throughout the plant?
		What environmental conditions are relevant?
		What mechanisms are in place to respond to environmental conditions?
	How is energy consumed in buildings?	What patterns are there in consumption (spatially, temporally, etc.)?
		What environmental conditions are relevant to consumption patterns?
		What social conditions are relevant to consumption patterns?
	How can technological systems communicate energy supply and demand?	How can smart grid technology be leveraged?
		How can smart appliance technology be leveraged?
		What kind of interface would be necessary to manage multidirectional supply and demand information?
	How do people interact with energy systems?	
Anticipated findings	Energy management technology with a strong focus on human behavior change and educational component	

Table 16. Outline for Recommended Research Topic 3
Developed by author

One research path would be to further the investigation of the Pecan Street project in Austin with a biomimetic lens. According to the Environmental Defense Fund, one of the partners coordinating the project:

> In a typical Pecan Street home of the future, appliances will talk to each other and to the grid, which will be constantly adapting to changes in supply and demand. Residents will program their dryers and hot water heaters to run when energy is cheap, or when the energy source is renewable, like solar or wind” (Environmental Defense Fund).

Much of this work is still being developed, and inserting a biomimetic frame while these ideas are still being tested might lead to an even more effective solution. Improved information systems supporting a biomimetic solar energy system does not end with smart appliances – larger scale smart grid applications are also potentially important.

Based on the review of efficiencies of current and emerging photovoltaic energy technologies, it is unlikely that solar energy will be able to provide sustainable energy as defined in this study without a serious improvement in energy efficiency in buildings. There is potential for biomimicry to inform the research and implementation of energy efficient building technologies. Plant responses to long term reduced photosynthetically active radiation, drought, and other common stressors in which plants scale back metabolic activity is one potential connection that could be studied in further research.

Topic 4: Smart grid that mimics information distribution in ecosystems

The deployment of smart grid technology is well underway, however, as it is developed, there is potential to link it to ideas of biomimicry to make it an even more powerful tool for approaching sustainability. The 'smart grid' at its essence is a reimagining of the energy delivery system that allows for two-way communications between the devices within the system and those that are managing the system: devices within the system to both gather data and can be controlled at a central location (US Department of Energy). When the initial planning for the smart grid began in the Office of Electricity Delivery & Energy Reliability in 2005, they envisioned a system that uses digital technology to improve reliability, resiliency, flexibility, and efficiency (US Department of Energy).

This early conception had already outlined several functional characteristics consistent with a biomimetic energy system including self-healing abilities and resiliency through diverse connections and storage capabilities. Smart grid activities first gained legislative backing in 2007 with Title XII of the Energy Independence and Security Act of 2007 (EISA) (US Department of Energy). Further research on the ways in which the support of the federal (and where applicable, local) government continues to help the development of smart grid technologies could become a basis for government-backed biomimicry research. This further research would require the collaboration of biologists, building scientists, urban planners, and electric engineers.

Topic	Smart grid that mimics information distribution in ecosystems	
Research team	Biologist	
	Building scientist	
	Electrical engineer	
	Urban planner	
	Energy policy specialist	
Key questions	How does energy move through an ecosystem?	How much energy could be produced given the available solar radiation?
		How much energy remains as biomass?
		What percentage is used to fuel other species up the trophic levels?
		How much diversity is there in the paths that energy could take?
		How is the distribution of energy prioritized (competition, predation, mutualism)?
	How is energy consumed?	
	How is energy produced?	
	What are the current regulations around sharing energy?	
Anticipated findings	Recommendations for the design and implementation of smart grid technologies	

Table 17. Outline for Recommended Research Topic 4
Developed by author

Topic 5: Growing your photovoltaic array

As discussed in the previous chapter there is great potential for biomimicry to inspire not only the physical artifacts found in photovoltaic systems, but also to inspire the growth of the industry over time and across the landscape. There are several small scale models already in existence demonstrating the ability for energy produced and capital gains to fuel the growth of photovoltaic arrays (Perlin, From Space to Earth: The Story of Solar Electricity, 1999). As in plants and the photosynthetic process, the products of photovoltaic processes should be first allocated to the production of more energy-producing technology until the socio-technological system that the array supports can sustain function with the energy produced using photovoltaics. This study would involve collaboration between biologists, ecologists, energy policy specialists, and economists, among others. The key questions at the core of this direction of research and the anticipated findings are listed in Table 18.

Topic	Photovoltaic process that mimics photosynthesis	
Research team	Biologist/Ecologist	
	Energy policy specialist	
	Economist	
Key questions	How do plants grow?	What ratios of energy produced is allocated to each area of the plant?
		What are the functions of each of these areas?
		How do environmental conditions affect the process of allocating energy?
	What are the energy demands of photovoltaic production?	What is the ratio of energy input in the manufacture of a photovoltaic panel to lifetime energy produced by the same panel?
		Is it reasonable to rely on solar energy to produce photovoltaic panels?
		How do the energy demands of emerging technologies compare to the energy demands of producing conventional photovoltaics?
	In what, if any, commercial, industrial, or residential context would this model make economic sense?	
	Are there potential policy changes that could support the 'grow your array' model?	
Anticipated findings	The feasibility or infeasibility of the 'grow your PV array' model	

Table 18. Outline for Recommended Research Topic 5

In addition to the federal funding and other resources going toward research and education around smart grid technologies, there are characteristics of the local social, economic, and political conditions that should influence the developmental path of a biomimetic solar energy system. A complete review of the photovoltaic market in the region as it relates to national and international markets might reveal opportunities for growing photovoltaic arrays in local conditions. Surveying the attitudes of individuals in local communities may reveal opportunities as well. In addition to the federal policies around renewable energy technologies and smart grid activities, local policies and incentive programs should be reviewed to identify opportunities for growing the photovoltaic array.

Regardless of the direction of research, biomimetic approaches to problem-solving should always involve interdisciplinary – or transdisciplinary – cooperation and the constant reminder of the importance of envisioning solutions as both being situated in larger systems and containing smaller systems within themselves.

8.3 Final thoughts

As seen throughout this thought experiment, there is great opportunity for biomimicry to become a path to environmental sustainability with promise for more equitable and economic design as well. There are many possible paths by which to achieve biomimicry as seen in this chapter and throughout this thesis, but the core to biomimetic design toward a sustainable goal is interdisciplinary cooperation. As Janine Benyus expresses, biomimetics "work at the edges of their disciplines, in the fertile crests between intellectual habitats" (Benyus, 1997, p. 4). The design and construction of a space, whether virtual or physical, to become a biomimetic's habitat is necessary to facilitate open collaboration to occur between individuals of all relevant disciplines in natural science, design, technological development, policy, behavioral science, economics, and beyond. It is my hope that the ideas in this thesis will lead others to see the value in transdisciplinary problem solving and inspire others to consider biomimicry as a potential path to a sustainable future.

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